CRITICAL APPRAISAL OF DIFFERENT DROUGHT INDICES OF DROUGHT PREDECTION & THEIR APPLICATION IN KBK DISTRICTS OF ODISHA

A

DISSERTATION

SUBMITTED IN PARTIAL FULFILMENT OF THE REQUIREMENTS FOR THE AWARD OF THE

DEGREE OF

MASTER OF TECHNOLOGY

IN

CIVIL ENGINEERING

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DEPARMENT OF CIVIL ENGINEERING

NATIONAL INSTITUTE OF TECHNOLOGY

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WATER RESOURCES ENGINEERING

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2014

CERTIFICATE

This is to certify that the thesis entitled " ***Critical Appraisal Of Different Drought Indices Of Drought Prediction & Their Application In KBK Districts Of Odisha****", being submitted by Sri* ***Bibhuti Bhusan Sahoo*** *to the National Institute of Technology Rourkela, for the award of the Degree of Master of Technology of Philosophy is a record of bona fide research work carried out by him under my supervision and guidance. The thesis is, in my opinion, worthy of consideration for the award of the Degree of Master of Technology of Philosophy in accordance with the regulations of the Institute. The results embodied in this thesis have not been submitted to any other University or Institute for the award of any Degree or Diploma.*

The assistance received during the course of this investigation has been duly acknowledged.

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Abstract:

Mapping of the extreme events (droughts) is one of the adaptation strategies to consequences of increasing climatic inconsistency and climate alterations. Drought is one of the short-term extreme events. There is no operational practice to forecast the drought. One of the suggestions is to update mapping of drought prone areas for developmental planning. Drought indices play a significant role in drought mitigation. Many scientists have worked on different statistical analysis in drought and other climatological hazards. Many researchers have studied droughts individually for different sub-divisions or for India. Very few workers have studied district wise probabilities over large scale. In the present study, district wise drought probabilities over KBK (Kalahandi-Balangir-Koraput) districts of Odisha, which are seriously prone to droughts, has been established using meteorological, hydrological and remote sensing based agricultural droughts indices. The meteorological droughts indices are: percentage departure, percentage to normal, percentile, Standard Precipitation index (SPI), Reclamation Drought Index (RDI), Effective drought index (EDI), and Aridity Index (AI). The hydrological drought indices are: Streamflow drought index (SDI), Surface water supply index and proposed drought severity index (PDSI). The satellite data based agricultural drought indices was Normalized Difference Vegetation Index (NDVI). Mapping for moderate and severe drought probabilities for KBK districts has been done and regions belonging different class intervals of probabilities of drought have been demarcated. Such type of information would be a good tool for planning purposes and for input in modelling. Moreover, the present work discusses (a) composite drought indices with the combinations of meteorological, hydrological and satellite data based agricultural drought index, and (b) development of a proposed hydrological drought index.

Keywords: Drought indices, composite drought index, SPI, RDI, DSI, NDVI

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LIST OF ABBRIBIATIONS

Q90- stream flow is at least this high 90 percent of the time

Q75 - stream flow is at least this high 75 percent of the time

σ -Standard Variation

AI-Aridity Index

AWiFS -Advanced Wide Field Sensor

AISMR -All-India Summer Monsoon Rainfall

FAO- Food and Agriculture Organization

EDI- Effective drought index

IMD- India Meteorological Department

IR- Infra-Red

KBK-Koraput, Balangir and Kalahandi

MAP-Mean Annual Precipitation

MOA-Ministry of Agriculture

MODIS- Moderate Resolution Imaging Spectroradiometer

NOAA -National Oceanic and Atmospheric Administration

NDVI- Normalized Drought Vegetation Index

NIR-Near Infra-Red

PDSI-Proposed Drought Severity Index

PET-Potential Evapotranspiration

RDI- Reconnaissance Drought Index

SDI-Streamflow Drought Index

SPI-Standardized Precipitation Index

SWSI -Surface Water Supply Index

UNESCO- United Nations Educational Scientific and Cultural Organization

WMO- World Meteorological Organization

CHAPTER 1

INTRODUCTION

1.1 Background

Al most one third of the world's population exists in a zone with water deficiencies, and nearly one billion lack access to safe drinking water. Worldwide, drought (7.5 %) is considered as the second-most geographically widespread hazard after floods (11 %) of the earth's terrestrial area. The percent of area influenced by serious drought has doubled from 1970s to the early 2000 (Nagarajan 2009).Out of the total geographical area of India, almost one-sixth area with 12% of the population is drought prone; the areas that receive an annual precipitation up to 60 cm are the most drought prone. The Irrigation Commission (1972) had acknowledged 67 districts of different states in India as drought prone. These cover 326 talukas located in 8 states, covering an area of 49.73m ha. Subsequently, the National Commission on Agriculture (MOA 1976) recognized a few more drought prone areas with marginally distinctive criteria. Successively, based on comprehensive studies, 74 districts of the country have been identified as drought prone.

1.2 History of Drought in India and Odisha

In India, about 68% of the area is susceptible to drought in varying degrees. Of the entire area, 35% of the area, which receives precipitation between 750 mm and 1,125 mm, is considered drought-prone, whereas another 33%, which receives less than 750 mm of precipitation, is called chronically drought-prone.

The drought of 1965-67 and 1979-80 affected comparatively high rainfall areas, the drought of 1972, 1987, and 2002 affected mostly semi-arid and sub-humid regions. In recent years, central, north-west and peninsular India suffered frequent droughts. These are low rainfall zones and the frequent failure of monsoon aggravates the intensity of droughts in these regions.

In India drought-prone areas comprise a total land area of 329 million hectares, with three-fourths being arid, semi-arid and sub-humid areas.

Arid zone (19.6%): Mean annual precipitation (MAP) of 100- 400 mm (water deficit throughout the year); Rajasthan, parts of Haryana and Gujarat. Droughts are severe in this zone.

Semi-arid zone (37.0%): MAP of 400- 600 mm (water surplus in some months and deficit in other months); parts of Haryana, Punjab, west Uttar Pradesh, west Madhya Pradesh, and also most of the peninsular parts of the Western Ghats. Drought can be moderate to severe in this zone.

Dry sub-humid zone (21.0%): MAP of 600- 900 mm in India; parts of northern plains, central highlands, eastern plateau, parts of Eastern Ghats and plains and parts of western Himalayas. Droughts are moderate in this zone.

Humid and per-humid regions, such as Assam and other north-east States rarely face drought.

1.2.1 Drought Years:

There were 24 major drought years during the period 1871-2009 .1873, 1877, 1899, 1901, 1904, 1905, 1911, 1918, 1920, 1941, 1951, 1965, 1966, 1968, 1972, 1974, 1979, 1982, 1985, 1986, 1987, 2002, 2004, and 2009.These years defined as years with All-India Summer Monsoon Rainfall (AISMR) June to September, less than one standard deviation below the mean (i.e., anomaly below -10%). (Figure 1.1)

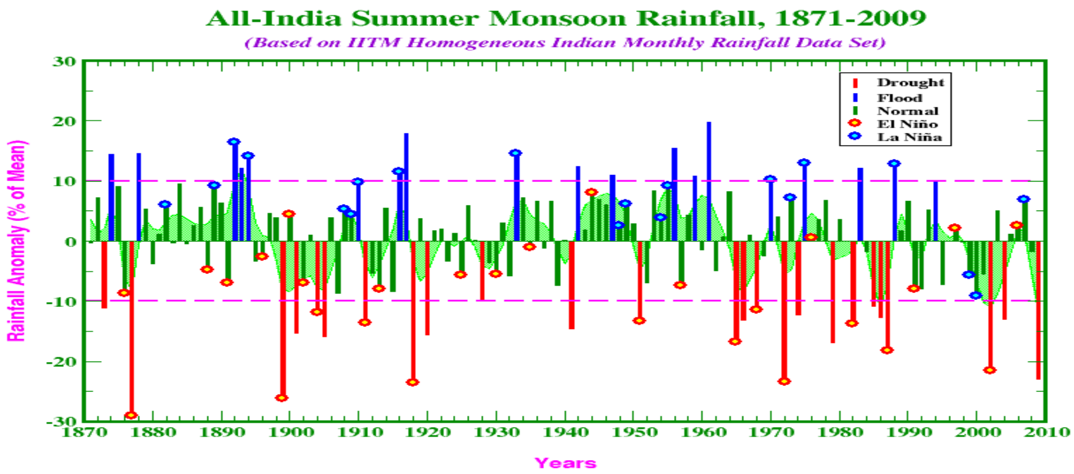

Figure 1.1: Rainfall anomalies over India

Most of the drought-prone areas are found in arid, semi-arid, and sub-humid regions of the country, which experience less than average annual rainfall (Figure1.2). Broadly, the drought-affected areas in India can be divided into two tracts. The first tract comprising the desert and the semi-arid regions covers an area of 0.6 million sq. km. It is rectangle shaped area whose one side extends from Ahmedabad to Kanpur and the other from Kanpur to Jullundur. In this region, rainfall is less than 750 mm and at some places it is even less than 400 mm. The second tract comprises the regions east of the Western Ghats up to a distance of about 300 km from coast. Known as the rain shadow area of the Western Ghats, rainfall in this region is less than 750mm and is highly erratic. This region is densely populated and frequent droughts cause considerable suffering, distress along with economic instability.

Besides these two tracts of scarcity, there are many pouches of drought in India. Some of these are:

- Tirunelveli district, south of Vaigai River in Tamil Nadu
- Coimbatore area in Kerala

- Saurashtra and Kutch regions in Gujarat
- Mirzapur plateau and Palamu regions in Uttar Pradesh
- Purulia district of West Bengal
- Kalahandi region of Orissa.

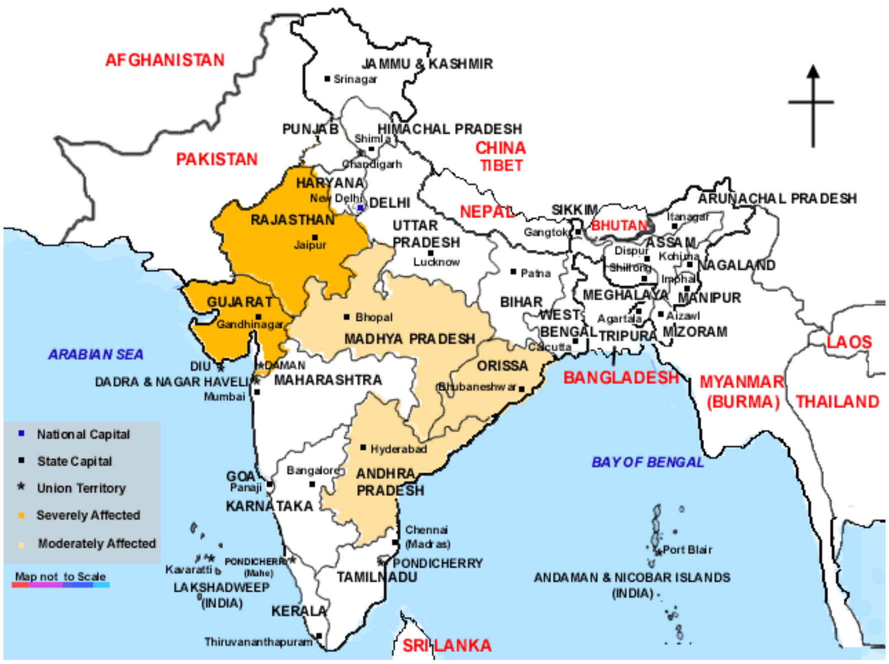

Figure 1.2: Drought prone areas in India

Together, these scattered pockets occupy an area of 0.1 million sq. km. Drought is a recurrent phenomenon in Andhra Pradesh where no district is entirely free of droughts. Rajasthan is one of the most drought prone areas of India. Eleven districts of the state are in arid regions including Jaisalmer as the driest district. No perennial river flows in Jaisalmer. Groundwater level in the district is 125–250 ft deep and at some places 400 ft deep. The rainfall in the district is extremely low at 164 mm. Out of 365 days of a year, on an average 355 days are dry. The total area which receives inadequate rainfall is just over one million sq. km. The regions with rainfall less than 400mm occupy 12% of the total geographical area, and the area below 750mm rainfall is 35% or a little over a third of the country. Thus out of the total gross cultivated area of the country, 56 million ha is subject to inadequate and highly variable rainfall. Large areas in the four states that utilize Narmada water falls in arid and semi-arid regions. Nearly 57% of Rajasthan and 32% of Gujarat falls in arid zone. Also, nearly 61% of Maharashtra and 46% of the area of Gujarat is semi-arid. This shows how important it is for these states to properly use available water.

1.2.2 Drought in Odisha

Drought is seems to be a consistent phenomenon in the state Odisha and every year some or the other parts of the state are affected by it. Looking at the frequency and geographical spread of drought, the districts such as undivided Kalahandi, Balangir and Koraput districts are more vulnerable. A decade and half ago drought was confined only to the KBK districts of Odisha, but today this has almost become a state wide calamity.

1.3 Drought Definition

There is no clear definition of drought; it only depends on the context and regions. Scientist over time tried to define this phenomenon, but still there is no clear definition. The primary cause of any drought is a deficiency in rainfall and, in particular, the timing, distribution, frequency and intensity of this deficiency in relation to the existing water storage, demand, and use. This deficit can result in an unavailability of water essential for the functioning of a natural (eco-) system and/or indispensable for a certain human activities. Appendix –I shows the definition of drought given by different scientists over a period of time.

1.3.1 Conceptual Definitions of Drought

Conceptual definitions, expressed in general terms, help people understand the concept of drought. For example, drought is a protracted period of deficient precipitation resulting in extensive damage to crops, further resulting in loss of yield. Conceptual definitions may also be important in establishing drought policy.

1.3.2 Operational Definition of Drought

An operational definition of drought helps people to identify the beginning, end, and degree of severity of a drought. This definition is usually made by comparing the current situation to the historical average, often based on a 30-year period of record (according to World Meteorological Organization recommendations). The following categories of drought are usually considered (Wilhite and Glantz 1985; AMS 2004; Hennessy et al. 2008):

1.3.3 Meteorological

Meteorological drought is usually defined on the basis of the degree of dryness (in comparison to some "normal" or average amount) and the duration of the dry period (WMO, 2005; Schuman, 2007). Definitions of meteorological drought must be considered as specific to a region since the atmospheric conditions that result in deficiencies of precipitation are highly variable from region to region.

1.3.4 Hydrological

Hydrological drought is associated with the effects of periods of precipitation (including snowfall) shortfalls on surface or subsurface water supply (i.e., stream flow, reservoir and lake levels, groundwater). The frequency and severity of hydrological drought is often defined on a watershed or river basin scale.

Although climate is a primary contributor to hydrological drought, other factors such as changes in land use (e.g., deforestation), land degradation, and the construction of dams all affect the hydrological characteristics of the basin.

1.3.5 Agricultural

Agricultural drought links various characteristics of meteorological (or hydrological) drought to agricultural impacts, focusing on precipitation shortages, differences between actual and potential evapotranspiration, soil water deficits, reduced groundwater or reservoir levels, and so forth.

1.3.6 Socioeconomic

This occurs when physical water shortage starts to affect people, individually and collectively or, in more abstract terms, most socio-economic definitions of drought are associated with the supply and demand of an economic good.

1.4 Impacts of Drought

All the definitions are related to the impacts of a dry spell on the human activities: the impacts of drought may be environmental, economical and social.

1.4.1 Environmental Impact

The environmental impact is the result of damages to plant and animal species, wildlife habitat, air and water quality; forest and fires, degradation of landscape quality; loss of biodiversity, and soil erosion. Some of the effects are only short-term and normal conditions are quickly re-established. Other environmental effects linger for some time or may even become permanent. For example, the degradation of landscape quality, including increased soil erosion, may lead to a permanent loss of biological productivity of the area.

1.4.2 Economical Impact

The economical impact occurs in agriculture and related sectors, including forestry and fisheries, which depend on the surface and groundwater supplies. In addition to obvious losses in yields in both crop and livestock production, drought is associated with the increase in insect infestations, plant disease, and wind erosion.

1.4.3 Social Impact

The social impact is present in periods of extreme, persistent drought. In these cases some emergency sources of water are required to take safety measure to safeguard public health.

1.5 Drought Assessment And Its Need

The quantification of drought severity is called as drought assessment. Drought assessment can be done with the use of a suitable drought index. The drought index selection depends upon the application of drought assessment. It could be meteorological, hydrological or Agricultural drought assessment. Remote sensing derived drought indices could aid a helping hand in this context.

1.6 Problem Statement

KBK districts of Odisha becomes the headlines in newspapers for the frequent drought situation that has broken the economic strength of the cultivators. A long history of drought covering more than a century in Kalahandi has occurred. Drought had occurred in Kalahandi in 1868, 1884 and 1897 following a famine in the year 1899. This famine left an abysmal socio-economic gloom in this area. The terrible drought of 1965–66, which occurred in Kalahandi, totally broke down the economic backbone of the people. Due to lack of rain, three-fourth crop production failed. The effect of the drought continued to be felt in 1967.A series of drought in 1922–1923, 1925–1926, 1929–1930, 1954–1955, 1955–56, 1974–75 1985-86, 1986-87, 1988-89, 1992-93, 2002-03, 2008-09 and 2010-11 occurred in Kalahandi. Same is the case with the undivided Bolangir district. There was famine in 1899-1901. The other years of drought in that district were 1935-36, 1954-55, 1965-66 and the late 1980s and 1990s. Even after that also this zone has not got respite and has witnessed drought condition almost at regular intervals. Drought, semi drought like condition, total or partial crop loss, long dry spells continues even today.

1.7 Objectives

- Critical review of different drought indexing methods (meteorological, hydrological and agricultural) used globally and in India.
- Application of meteorological, hydrological and agricultural based drought assessment techniques in KBK districts of Odisha
- Development of a proposed drought severity index based on hydrological data.
- Development of composite drought indices with the combinations of meteorological, hydrological and satellite data based agricultural drought.
- Mapping for moderate and severe drought probabilities for KBK districts and demarcation of regions belonging different class intervals of probabilities of drought

CHAPTER 2
LITERATURE REVIEW

2.1 Drought Indices

A drought index value is typically a single unit less number, far more useful than raw data (rainfall, snowpack, stream flow, and other water supply indicators) for decision making. The Government of India, State Governments and the scientific community uses a number of indices to measure the intensity, duration, and spatial extent of drought (Ministry of Agriculture, 2009). It is useful to also refer to these scientific indices for monitoring drought situation at the National and State levels.

2.2 Critical Appraisal of Drought Indices

There are more than 150 drought indices exists and many more new indices come into account in the last decades and not only many drought indices are developed every year across the globe but also an sincere attempts also have been made reviewing the drought indices and the different climatic parameters such as precipitation ,soil moisture , vegetation moisture, land surface temp, humidity, land cover change etc which plays direct or indirect role in development of drought indices: examples: (Heim, 2000) (Hayes et al. 2007), (Wang & Qu 2009), (Mishra & Singh 2010), (Zhang et al, 2010), (Zargar et al, 2011) & improving the existing ones.

However, selection strongly depends upon the requirement like availability of resources/data, field of application of interest, specific boundary conditions, and according to the necessity of spatial or temporal resolution. Some drought indices specifically reflect one type of impact or application, while others can be configured to correspond to varying impacts and thus drought type. For example, SPI, which is a meteorological drought, can be deployed for longer time scales to reflect agricultural and hydrological droughts/impacts (Zargar et al, 2011). Experts participating in the Inter-Regional Workshop on Indices and Early Warning Systems for Drought, held at the University of Nebraska-Lincoln, USA, 2009 made a significant step through a consensus agreement that the Standardized Precipitation Index (SPI) should be used to characterize meteorological droughts by all National Meteorological and Hydrological Services around the world. Traditional indices calculated from meteorological observations (point-based) are insufficient to monitor drought at regional scale. Remote sensed data is able to provide spatial information on drought event repeatedly at a lower cost, and has been playing an increasingly important role in drought monitoring for the past decades (Li et al, 2012). Satellite-based drought indices have obvious advantages compared to station-based meteorological drought indices in spatial resolution (Zhou et al, 2013) along with large spatial coverage.

2.3 Traditional Drought Indices:

Van Rooy (1965) developed a drought anomaly index based on the ratios of rainfall departure from normal to the departure of threshold value from normal. The threshold value was taken as the average of the lowest ten values in series.

Palmer (1965) developed a general methodology for evaluating the meteorological anomaly in terms of in index which permits time and space comparisons of drought severity. He developed Palmer Drought Severity Index (PDSI), which was one of the first procedures to demonstrate success at quantifying the severity of droughts across different climates. The index has been used to illustrate the areal extent and severity of various drought episodes (Palmer, 1967; Karl and Quayle, 1981) and to investigate the spatial and temporal drought characteristics (Lawson et al., 1971; Klugman, 1978; Karl and Koscielny, 1982; Diaz, 1983; Soule, 1993; Jones et al., 1996).

The PDSI is a two layer moisture model. Palmer introduced the concept of CAFEC (Climatically approximate for the existing conditions) rainfall, which was normal for a given place. The anomaly between the CAFEC and actual precipitation is used as a drought indicator. To make this anomaly comparable in space and time, it is multiplied by a weighting factor K which depends on average moisture demand and supply and mean of the absolute values of anomaly of the place. The classification of drought intensity based on Palmer drought index is +4 representing extremely wet and -4 representing extremely dry conditions.

PDSI is highly sensitive to temperature and precipitation anomaly. PDSI is perhaps the most widely used regional drought index for monitoring droughts still it has some limitations. The limitations of PDSI have been documented in several studies (Alley, 1984; Karl and Knight, 1985; Willeke et al., 1994; McKee et al., 1995; Guttman, 1997). Limitations of PDSI include: (1) an inherent time scale making PDSI more suitable for agricultural impacts and not so much for hydrologic droughts, (2) assumptions that all precipitation is rain, thus making values during winter months and at high elevations often questionable. PDSI also undertakes that runoff only occurs after all soil layers have become saturated, leading to an underestimation of runoff, and (3) PDSI can be slow to respond to developing and diminishing droughts (Hayes et al., 1999).

Palmer hydrological drought index (PHDI) a derived from PDSI but it is more insistent to consider a drought end. The drought ends only when the ratio of moisture received to moisture required is 1. It measures hydrological impacts of drought (e.g., reservoir levels, groundwater levels, etc.) which take longer to progress and longer to improve from. This long-term drought index was developed to measure these hydrological effects, and it responds more deliberately to changing conditions than the PDSI.

In the year 1968 Palmer developed crop moisture index (CMI) to evaluate short-term moisture conditions (week to week) across major crop growing regions. Calculation of CMI involves the use of weekly values of temperature and precipitation to calculate a simple moisture budget.

CMI is a derivative of PDSI which was developed from moisture accounting procedures as the function of the evapotranspiration irregularity and the moisture extremes in the soil. It also can be present as the monthly moisture anomaly or Z index as a product from PDSI calculation. It can detect drought sooner than PDSI and PHDI. CMI looks at the top 5 feet of the soil layer. It recognizes potential agricultural droughts. CMI is restricted to use only in the growing season. It cannot determine the extended term period of drought.

While the PDSI and its derivate have been appraised and criticized in numerous studies (e.g Alley, 1984), several authors proposed developments of the PDSI until today, such as for operational purposes, a real time version of PDSI, called Proposed PDSI (PDI), was introduced by Heddinghaus and Sahol (1991). the self-calibrated PDSI (Wells et al., 2004), or a PDSI with Proposed potential evapotranspiration derivation, replacing the original, but arguable Thornthwaite method by a Penman-Monteith term (e.g. Burke et al., 2006) or a Priestley-Taylor formulation (Mavromatis, 2007).

Gibbs and Meher (1967) made a study of drought in Australia by using annual rainfall deciles as drought indicator. Using a network of 100 stations, maps have been prepared showing the decile ranges in which rainfall for each year has occurred.

The Bhalme-Mooley Drought Index (BMDI) (Bhalme and Mooley, 1980) provides a good measure of the current status of drought that is the effect of small periods of dry weather, unlike the PDSI which is aimed to evaluate the degree of severity and frequency of persistent periods of abnormally dry conditions. BMDI is simple and less complex than other indices because it is not involving terms such evapotranspiration or soil water capacity, which are factors mainly difficult to estimate and it is based only in monthly precipitation.

Surface Water Supply Index (SWSI) Shafer and Dezman (1982) developed form the Palmer Index to take into account the mountain snowpack it represents surface water supply conditions and includes water management. Simple calculation combines hydrological and climatic features. It Considers reservoir storage management dependent and unique to each basin, which limits inter-basin comparisons does not represent well extreme events. SWSI is used for frequency analysis to normalize long-term data such as precipitation, snow pack, stream flow, and reservoir level. The best suitable area of this particular hydrological drought index to work out is the mountainous regions.

Guttman (1991) examined the sensitivity of PHDI to departure from average temperature and precipitation condition. A time series of zero index value was calculated and then one monthly temperature or precipitation index of one anomalies value. Independent series were calculated for temperature anomalies plus and minus 1, 3, 5 and 100 F and for precipitation anomalies of 25, 50, 75,125,150 and 200% of normal, for each calendar month for Colorodo ,Indiana, Nevada, New York, Oklahoma , South Dakota Washington and Wisconsin. Analysis of time series showed that the period of time required for the index to replicate actual rather than artificial initial condition more than four year. It was found that the result of temperature anomalies are significant compared to the effect of precipitation anomalies. In some cases one anomalous precipitation value could result in established wet or dry spells that may last for up to two years.

McKee et al., (1993) standardized precipitation index (SPI) for any location is calculated, based on the long-term precipitation record for any desired period. This long-term record is fitted to a probability distribution, which is then transformed to a normal distribution so that the mean SPI for the location and desired period is zero. The major asset of SPI is that it can be calculated for a variety of time scales. This flexibility permits SPI to monitor short-term water supplies, such as soil moisture which is important for agricultural production, and long-term water resources, such as groundwater supplies, stream flow, and lake and reservoir levels. Soil moisture conditions respond to precipitation anomalies on a relatively short scale whereas groundwater, stream flow, and reservoir storage reflect the long term precipitation anomalies.

The Standardized Precipitation Index (SPI) has found widespread application (McKee et al., 1993; Heim, 2000; Wilhite et al., 2000; Rossi and Cancelliere, (2002). Guttman (1998) and Hayes et al. (1999) compared SPI with Palmer Drought Severity Index (PDSI) and found that the SPI has advantages of statistical consistency, and the ability to describe both short-term and long-term drought impacts through the different time scales of precipitation anomalies than the PDSI. Cancelliere, (2007) used stochastic methodologies to compute drought transition probabilities, based on the SPI index and forecasted drought condition in Sicily.

Some of the agricultural drought indices are the Soil Moisture Drought Index (SMDI; Hollinger et al., 1993) or the Crop Specific Drought Index (CSDI; Meyer et al., 1993), with applications to corn (Meyer et al., 1993) and soybean (Meyer and Hubbard, 1995).

Weghorst (1996) proposed the Reclamation Drought Index (RDI) for the operational detection of drought events and for the initiating of relief, if a certain severity level was reached. The RDI takes into account air temperature for the demand side, and precipitation, reservoir storage, streamflow, and snow pack for the supply side, as well as the duration of a drought event. Opposite to the two new agricultural drought indices, the focus of the RDI is to identify onset and end of a drought period in a more conservative way, i.e. not taking into account short term variations. As a result, although also computed on a monthly basis, the RDI behaves more slowly even compared to the PHDI.

Stahl (2001) developed a Regional Streamflow Deficiency Index (RDI) to detect regional drought events from time series of measured discharge data. This two-step methodology firstly computes a deficiency indicator from individual streamflow time series, taking into account the 90% exceedance threshold (Q90) derived from the flow duration curve. In a second step, the deficiency sign of an individual gauging station is compared to the neighboring stations of the region. Only if a substantial number of stations show a like pattern of low flows, a regional drought event is detected. This methodology has been applied in France by Prudhomme and Sauquet (2007).

Keyantash and Dracup (2004) proposed a multivariate Aggregate Drought Index (ADI) which considers information from meteorology (precipitation), hydrology (streamflow, reservoir storage), and land surface (evapotranspiration, soil moisture, snow water content). Measured data input is preferred to simulation results, which is however not always possible, especially in the case of soil moisture. The derivation of the ADI includes principle component analysis to extract the best indicator from the correlation of the input variables that explains the largest fraction of variance. In a test case for California, considerable correlation was found with the PDSI, although the ADI acted more conservative than the PDSI, as it takes more elements of the hydrological cycle into account to determine a drought situation. The authors describe the benefits of the ADI as the inclusive character and the straightforward mathematical formulation that allows for an operational application.

Narasimhan and Srinivasan (2005) developed soil moisture deficit index (SMDI) and evapotranspiration deficit index (ETDI) based on weekly soil moisture and evapotranspiration simulated by a calibrated hydrologic model, respectively. The drought indices were derived from soil moisture deficit and evapotranspiration deficit and scaled between -4 and +4 for spatial comparison of droughts, irrespective of climatic conditions. The proposed Soil Moisture Deficit Index (SMDI) is computed as the weekly soil moisture normalized by long-term statistics. Weekly values are then added on an incremental basis to account for the duration of a drought. The SMDI is computed separately for different soil depths in order to consider the varying rooting depth for different crops and stages of plant development. The Evapotranspiration Deficit Index (ETDI) is computed similar to the SMDI, but considers the water stress ratio of potential to actual evapotranspiration instead of soil moisture. These indices reflect short-term dry conditions, thus respond to agricultural drought.

Marletto et al. (2005) proposed another new agricultural drought index called DTx for regional application. It is based on the daily transpiration deficit as computed by a water balance model, and describes the integrated deficit of transpiration of a crop for a period of x days; e.g. DT180 indicates the deficit of the 180 precedent days. When compared to SPI this index showed advantages, as it takes into account not only the precipitation deficit, but also the effects of land use, soils, and especially the climatic conditions that govern the crop's transpiration.

Shukla and Wood (2008) derived standardized runoff index (SRI) which incorporates hydrologic processes that determine the seasonal loss in streamflow due to the influence of climate. As a result, on month to seasonal time scales SRI is a useful complement to SPI for depicting hydrological aspects of droughts.

2.4 Remote Sensing-Based Drought Indices:

The various remotely sensed data serves as input for the various methods, which are used for the identification, monitoring and assessment of the drought. It is facilitated by several satellite based indices like (NDVI, VCI, SVI, NDWI, CWSI, TCI, VHI, TVDI) in Visible, Near Infrared and Thermal Infrared and Microwave regions, to target and analyse the concerned areas. Among these, the NDVI is one of the most popular and globally accepted remote sensing indices for Agricultural drought.

In early 1980s with the development of Earth observation satellites equipped with sensors mainly in the optical domain opened a new era for drought monitoring and detection. The new technologies allowed for the derivation of truly spatial information at global or regional coverage with a consistent method and a high repetition rate. The several remotely sensed data serves as contribution for the various methods, which are used for the identification, monitoring and assessment of the drought .Numerous indices were developed to describe the state of the land surface, mainly of vegetation, with the potential to detect and monitor anomalies such as droughts. A good overview on the first generation of remote sensing based drought monitoring is given in Gutman (1990), while Kogan (1997) provides an update almost one decade later. It is facilitated by several satellite based indices like (NDVI, VCI, SVI, NDWI, CWSI, TCI, VHI, TVDI) in Visible, Near Infrared and Thermal Infrared and Microwave regions, to target and analyse the concerned areas among those the most noticeable vegetation index is undoubtedly the Normalized Difference Vegetation Index (NDVI; Tucker, 1979) that was first applied to drought monitoring by Tucker and Choudhury (1987). This study initiated several derivate for drought monitoring such as the Vegetation Condition Index (VCI; Kogan, 1990, 1995), the anomaly of the NDVI called NDVIA (Anyamba et al., 2001), or the Standardized Vegetation Index SVI (Peters et al., 2002).

Currently, NDVI products can be generated from the data of most of the satellite sensor systems. The MODIS NDVI of 250 m and 1000 m, SPOT VGT NDVI of 1000 m, NOAA AVHRR NDVI of 1000 m, IRS WiFS NDVI of 188 m and IRS AWiFS NDVI of 56 m are widely used for drought monitoring purpose because of the advantages of spatial and temporal coverage of these products.

National Drought Assessment and Monitoring System (NADAMS) is an example of effective use of AVHRR NDVI for drought assessment over India. While at global level, FAO have created Global Information and Early Warning System on Food and Agriculture (GIEWS), and is principally based on near real time AVHRR NDVI.

NASA's Terra and Aqua MODIS available from 1999 onwards providing data with improved sensitivity to vegetation than AVHRR, is a benefit. The spatial resolution of NDVI offered by MODIS is at 200m, 500 m and 1000m. Many fruitful applications of MODIS NDVI for drought monitoring and assessment had been attained. One of those success stories over Lower Mekong Basin on monitoring Agricultural drought is carried out by Son et al. (2012).

In addition to the information derived from the optical domain, also the thermal channels of Landsat Thematic Mapper (TM) and the Advanced Very High Resolution Radiometer (AVHRR) sensors were exploited, resulting in the retrieval of land surface temperature estimates (LST). Applying the thermal channels to drought monitoring, Kogan (1995) proposed the Temperature Condition Index (TCI). Most promising was the final combination of optical and thermal information into the Vegetation Temperature Index (VTI) or Vegetation Health Index VHI by Kogan (1997, 2000). Exploiting the strongly negative correlation between vegetation indices based on visible or near infrared information (predominantly NDVI) on the one hand and brightness or land surface temperature on the other hand for drought applications has been and is still a wide field of study Carlson et al. (1994), Moran et al. (1994), but also McVicar and Bierwirth (2001), Bayarjargal et al. (2006).

In addition to all the indices discussed above, some recently developed advanced remote sensing indices are Vegetation Temperature Condition Index (VTCI; Wan et al., 2004), Proposed Perpendicular Drought Index (MPDI; Ghulam et al., 2007c), Normalized Multi-Band Drought Index (NMDI; Wang and Qu, 2007).

2.5 Combined Drought Indices & Drought Modelling Scenario.

The latest generation of drought indices developed in the last decade tries to incorporate and exploit a maximum of information that is readily available and proofed to be useful in specialized drought indices. The combination of meteorological data with remote sensing derived land surface information is typical for this type of drought indices. This combination is already performed operationally on a manual basis within the US Drought Monitor (NDMC, 2008), however without a single reproducible quantitative drought index that comprises all information. The recently developed Vegetation Drought Response Index (VegDRI; Brown et al., 2008) is the first and prominent example and probably currently the most comprehensive drought index available. VegDRI combines NDVI datasets as derived from NOAA AVHRR with climate-based SPI and PDSI drought indices as derived from observations from selected stations of the synoptic network. It thus overcomes the deficiencies of either data source, i.e. for the NDVI the lack of discrimination of vegetation stress from sources other than drought, and for the climate data their dependence on the density of the network stations and the inevitable spatial interpolation of point station data. Additional static biophysical information such as elevation, landuse, soil water capacity, or percentage of irrigated agriculture is included in the derivation of VegDRI, too. The index was designed for operational near-real time use in the US with a spatial resolution of the underlying NDVI dataset of 1 km and a temporal update every 14 days. Due to its comprehensive character the computation of VegDRI is rather demanding with respect to data organization and processing. From all input data collected in a database three seasonal (spring, summer, autumn) linear regression models are built with which the final maps of VegDRI are produced. The index is currently under evaluation and will be made public within the next few years as an objective and operational drought monitoring tool at the US National Drought Mitigation Centre. According to Brown et al. (2008), the first results on 15 states in the central US compare qualitatively well to the manually generated Drought Monitor products.

An integrated drought monitoring system can be divided into five essential components: 1) determination of applicable climate indicators and resultant trigger levels; 2) identification of data requirements and data network sources; 3) acquisition and analysis of reliable data; 4) synthesis of the data and generation of practical, useful products (application); and 5) information dissemination (Svoboda 2002A), which include drought forecasting, probability based modeling, spatio-temporal analysis, and use of Global Climate Models (GCMs) for drought scenarios, land data assimilation systems for drought modeling, and planning.

For a comprehensive characterization of drought event a combination of different drought indices to develop a composite drought index has been progressively discussed as a way to integrate and more efficiently utilize readily existing information In report on to the Lincoln Declaration (WMO 2009), (Sivakumar et al, 2011) suggested the formation of a new composite hydrologic drought index that would cover stream flow, precipitation, reservoir levels, snowpack, and groundwater levels. The combination of drought indices from different domains seems to be the most promising, but also the most demanding way forward to draw a comprehensive picture of a drought situation (Niemeyer, 2008). In general, hybrid drought indices can provide a stronger correlation with actual impacts sustained in the ground (Zargar et al, 2011).

Hybrid models, incorporating large scale climate indices, seem to be promising for long lead-time drought forecasting (Mishra & Singh 2011).There are different simple simulation models, which can be used for predicting the characteristics and the impacts of droughts such as regression, autoregressive (AR) based models such as ARIMA (The autoregressive integrated moving average) as well as artificial neural networks ANNs. The ARIMA model approach has several advantages over others, such as moving average, exponential smoothing, neural network, and in particular, it’s forecasting capability and its richer information on time-related changes (Zhang, 2003).

ANNs can provide better promising results in estimate the linear and nonlinear behavior of complex systems. Application of such models to the composite drought index to examine their effectiveness is very essential in the field of drought mitigation.

Some of the applications of ANN models in drought forecasting include: Morid et al. (2007) predicted quantitative values of drought indices using different combinations of past rainfall, Effective Drought Index (EDI) and Standard Precipitation Index (SPI) in preceding months, and climate indices, such as SOI and NAO index as input layer.

Mishra and Desai (2006) compared linear stochastic models with recursive multistep neural network (RMSNN) and direct multistep neural network (DMSNN) for drought forecasting and observed that RMSNN was useful for short term drought forecasting, while DMSNN was useful for long-term drought forecasting.

In recent years there are also some composite drought indices developed for example US Drought Monitor; USDM (Svoboda et al., 2002) The USDM combines multiple indices such as PDSI and SPI as well as indicators such as vegetation and hydrologic conditions into a weekly drought map. Vegetation Outlook (VegOut) (Tadesse and Wardlow 2007), it integrate environmental biophysical information such as land cover type, irrigation status, soils, and ecological setting to climate information and RS observations of current vegetation conditions with oceanic index data and provide a future outlook of general vegetation conditions. VegDRI (Brown et al. 2008) it combines SPI and PDSI in addition to two NDVI-based indicators. Integrated Hybrid Drought Index (HDI) (Karamouz et al. 2009) combines SPI, SWSI, and PDSI, Scaled Drought Condition Index (SDCI) (Rhee et al, 2010), it combines NDVI and LST with precipitation data, Vegetation Water Supply Index (VWSI) (Cai et al. 2011) it combines LST and NDVI, Integrated Surface Drought Index (ISDI) (Zhou et al, 2013) combines the remotely sensed temperature information into the other input factors of the model.

Hybrid models are useful in extracting advantages of individual models for predicting droughts with better accuracy as well as for higher lead time in comparison to individual models (Mishra and Singh (2011).

Drought indices, derived over decades, have rainfall as a major parameter causing droughts (Mishra and Singh, 2010). Therefore long-lead drought forecasting is possible, if rainfall is predicted a long time in advance. Around the precipitation has been shown to be related to broad scale atmospheric globe, phenomena, such as El Nino-Southern Oscillation (ENSO), Sea Surface Temperature (SST), and Geopotential Height (GpH) (Ropelewski and Halpert, 1996). A relatively strong statistical relationship between ENSO, SSTs and rainfall has aroused considerable interest in long-range rainfall forecasting (Palmer and Anderson, 1994; Hastenrath, 1995; Goddard et al., 2001). However, the relation of large climate indices to rainfall varies from one region to another, for example, ENSO is a good indicator of droughts in Australia (Chiew and McMahon, 2002), but not necessarily in central and northern parts of Asia (Morid et al. (2006). Several studies demonstrated that ocean–atmosphere forcing by persistent Sea Surface Temperature (SST) influenced the timing of drought events, and their duration and magnitude over continental regions were largely governed by land–atmosphere feedbacks (Ferguson et al., 2010).

In order to have better drought forecasting, one should be able to forecast ENSO activities (e.g., Cane and Zebiak, 1985). Currently there are different approaches for ENSO prediction, for example: (i) statistical models, (ii) physical ocean models/ statistical atmosphere models, and (iii) physical coupled ocean/atmosphere models.

Using data mining techniques, Farokhnia et al. (2010) identified effective grids of Sea Surface Temperature (SST) and Sea Level Pressure(SLP) as predictors and using these as input to a hybrid model(Adaptive Neuro Fuzzy Inference System, ANFIS) to forecast possible droughts in Iran.

2.6 Drought Monitoring In India

The India Meteorological Department (IMD) prepares rainfall maps on sub-divisional basis every week throughout the year. These maps show the rainfall received during a week and corresponding departures from normal. During monsoon season, these maps are indicative of development of drought. In addition, IMD also provides the information on weekly rainfall and its deviation from normal at district level for the entire country. This information is useful to identify the districts with deficit/scanty rainfall and the prevailing meteorological drought. IMD also monitors drought using water balance technique which addresses agricultural drought.

The aridity index is calculated using the formula;

$$\text{Aridity Index} = \frac{(\text{Actual Evapotranspiration} - \text{Potential Evapotranspiration})}{\text{Potential Evapotranspiration}} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (1)$$

The departure of aridity index from normal percentage terms is used to define the various categories of drought severity. Anomaly up to 25 % is attributed to mild drought, 26-50% to moderate drought and >50% to severe drought. IMD has been bringing out weekly aridity anomaly charts from 1979 onwards, based on data from different observatories, covering south west monsoon period. These charts show the departures of actual aridity from normal aridity giving indication of the severity of water deficit to water demand relationship on weekly basis. IMD is also preparing detailed maps of rainfall, temperature (maximum and minimum), cloud cover, relative humidity and analyze this information with prevailing crop conditions and an Agromet Advisory Bulletin is prepared and disseminated to users.

Recent approaches & advances in drought study is highly a subject of concern for drought study. Due to the increase in drought scenarios during recent years across the globe it's quite essential to characterize drought and understanding drought properties for its mitigation. Drought indices play a significant role in drought mitigation across the different geographical regions in the world. Drought indices help in assessment of drought which is eventually very important for water resources planning and management. Therefore, understanding different drought indices essential for drought management operations. This above study presented in this paper could be very useful in future drought mitigation research across the world.

CHAPTER 3
THE STUDY AREA AND DATA COLLECTION

3.1 Geography And Extent

The KBK region of the state Odisha, India was selected as the study area for this research project (Figure 3). The undivided districts of Koraput, Balangir and Kalahandi (popularly known as KBK districts) have sine 1992-93 been divided into eight districts: Koraput, Malkangiri, Nabarangpur, Rayagada, Balangir, Sonepur, Kalahandi and Nuapada. These eight districts comprise of 14 Sub-divisions, 80 Tahsils, 80 CD Blocks, 1437 Gram Panchayats and 12,293 Villages. These districts have special status under the Revised Long Term Action Plan of Government of India. The total geographical area of the study area is approximately 47,646 Km^2. The socioeconomically underdeveloped KBK districts are located in the southwest part of Orissa (India) between latitudes 17°48’30``0N and 21°8`45``N and longitudes 81°22``48``E and 84°15`32``E in the Eastern Ghat range.

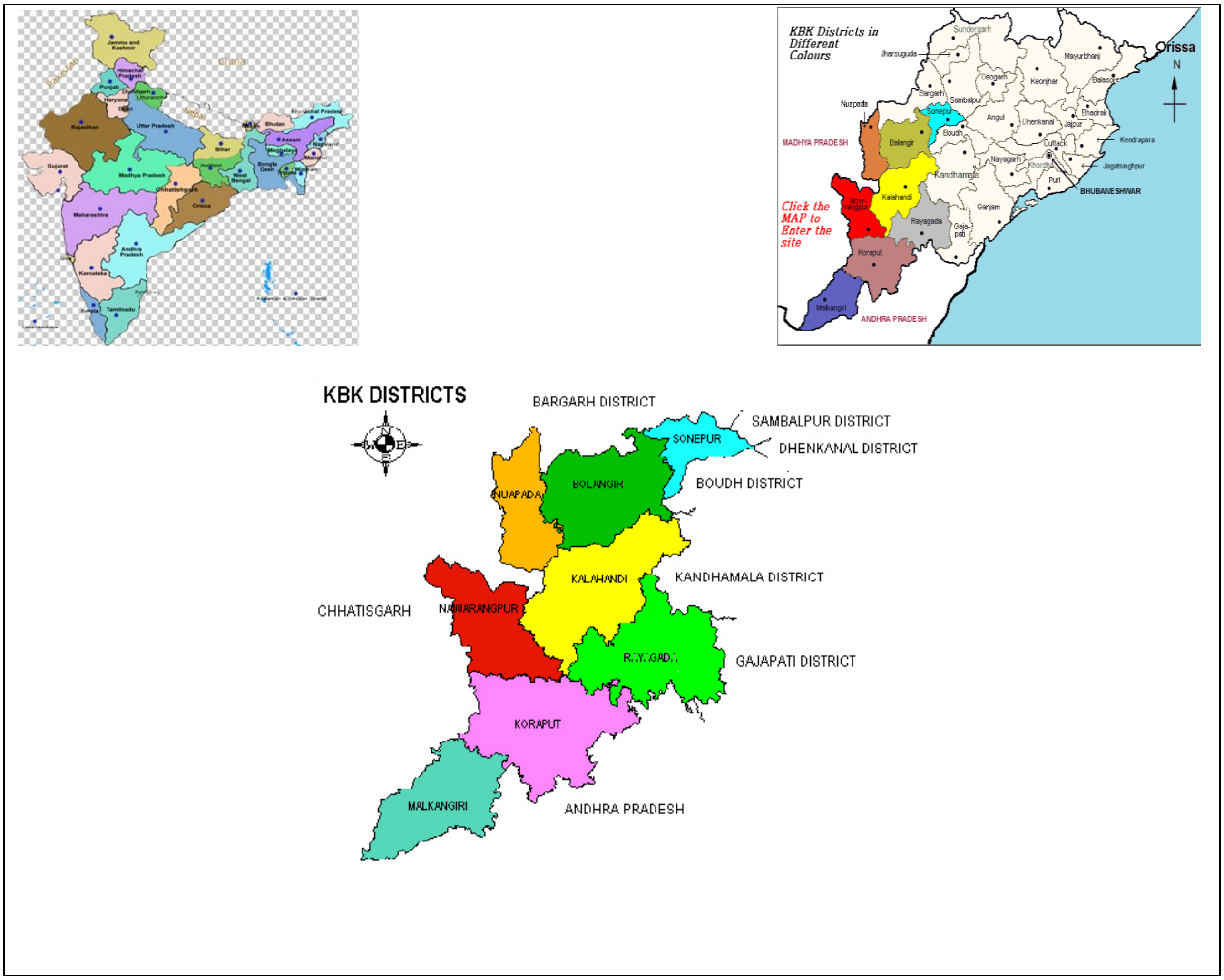

Figure 3.1: The study area-KBK Districts

3.2 Climate

The KBK region belongs to the sub-humid temperate region of India with an average rainfall ranging from 1100 to 1400 mm. Of the total annual rainfall, nearly 90% is received during the monsoon season (June–October) and the rest of the year remains nearly dry. The months of July and August are the wettest months of the year, receiving average rainfall of the order of 360 mm and 380 mm respectively. The southwest monsoon, which is the single largest contributor of monsoon rainfall in this region, normally sets in in mid-June.

The erratic nature of monsoon led to a rain fall of greater than 1100 mm in one month at some station where on the other hand, there is evidence of zero rainfall for seven or eight consecutive months in the study area. This region, therefore, often undergoes from both droughts and flash floods from time to time. But its exposure to drought is greater than floods because of the high variability of seasonal rainfall, dominant rain-fed paddy cultivation, and hilly terrain.

The climate is of extreme type, with May being the hottest month with mean daily maximum and minimum temperature of 42 °C and 31 °C respectively. December is the coolest month, with mean daily maximum and minimum temperature of 28 °C and 12 °C respectively.

3.3 Data Collection

Monthly rainfall, potential evapo-transpiration, and other related data for 112 years from all the eight rain gauge stations were collected from IMD, Indian water Portal, Moreover, daily discharge data for last 30 years collected from Central Water Commission for two sampling stations were also used for the analysis. For NDVI analysis, MODIS (Moderate Resolution Imaging Spectroradiometer) data is used. And the actual drought year data from Department of Agriculture, Odisha.

CHAPTER 4
METHODOLOGY

The drought analysis has been done using three categories based on; Meteorological data, Hydrological data and Remote sensing data.

4.1 Meteorological data based drought analysis

4.1.1 Percentage of departure from mean

This index is estimated using the following equation. If the departure of annual rainfall from normal (%) is 0 or above then there is no drought, 0 to -25 mild drought,-26 to -50 moderate droughts,-50 or more it's a severe drought situation.

$$P_d = \left[\frac{P_i - \overline{P}}{\overline{P}}\right] \times 100 \qquad \text{(2)}$$

Here, Pd is the percentage departure; Pi is the rainfall at any time and $\overline{P}$ is the mean rainfall This clearly indicates the departure of any precipitation events from its mean.

4.1.2 Percent of Normal

This index is computed by dividing the actual precipitation by the "normal" precipitation (typically considered to be a 30-year mean) and multiplying by 100. This index can be calculated for a variety of time scales. Usually these time scales range from a single month to a group of months. One problem is that the distribution of the precipitation, on time scales less than one year, is not Gaussian. For this reason the mean usually differs from the median. This introduces an error in the evaluation of the deviation from the values of the cumulated precipitation considered "normal" for a specific time-space scale. The equation for this index is:

$$I = \frac{<P>}{<P>_{30}} \times 100 \qquad \text{(3)}$$

Values of the index less than 100 means drought conditions exist.

4.1.3 Deciles

The distribution of the time series of the cumulated precipitation for a given period is divided into intervals each corresponding to 10% of the total distribution (decile). Gibbs and Maher (1967) proposed to group the deciles into classes of events as listed in the Table 1:

Table 1: Decile classification

Class	Percent	Period
Decile 1-2	20% lower	Much below normal
Decile 3-4	20% following	Below normal
Decile 5-6	20% medium	Near normal
Decile 7-8	20% following	Above normal
Decile 8-9	20% more high	Much above normal

4.1.4 Standardized Precipitation Index

The Standardized Precipitation Index (SPI) was developed by McKee et al (1993). The SPI is based only on precipitation. The SPI assigns a single numeric value to the precipitation, which can be compared across regions and time scales with markedly different climates. Jain et al. (2010) reported that there are a number of indices to quantify drought using meteorological data; however, the SPI is most widely used index. SPI can be calculated at different time scales and hence can quantify water deficits of different duration (Table 2). SPI was designed to show that it is possible to simultaneously experience wet conditions on one or more time scales and dry conditions at another time scale. These time scales reflect the impact of a drought on the availability of the different water resources. Soil moisture conditions respond to precipitation anomalies on a relatively short scale. Groundwater, streamflow, and reservoir storage reflect the longer-term precipitation anomalies. For these reasons, McKee et al. (1993) originally calculated the SPI for 3, 6, 12, 24, and 48 month time scales. The calculation of the index needs only precipitation record. It is computed by considering the precipitation anomaly with respect to the mean value for a given time scale, divided by its standard deviation. The precipitation is not a normal distribution, at least for time-scales less than one year. Therefore, the variable is adjusted so that the SPI is a Gaussian distribution with zero mean and unit variance. A so adjusted index allows comparing values related to different regions. Moreover, because the SPI is normalized, wet and dry climates can be monitored in the same way. The index calculation is based on the following expressions:

$$\mathrm{SPI} = \frac{X_i - X}{\sigma} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \text{(4)}$$

Where, X: the mean annual rainfall X_i the annual rainfall at any year. σ: the standard variation.

Table 2: SPI values and its indication on drought.

SPI values	Class
>2	extremely wet
1.5 to 1.99	very wet
1.0 to 1.49	moderately wet
-.99 to .99	near normal
-1.0 to -1.49	moderately dry
-1.5 to -1.99	severely dry
<-2	extremely dry

4.1.5 Reconnaissance Drought Index (RDI)

A new reconnaissance drought identification and assessment index was first presented by Tsakiris, 2004 while a more comprehensive description was presented in Tsakiris et al. (2006).

The index, which is referred to as the Reconnaissance Drought Index, RDI, may be calculated by the following equations. For illustrative purposes the yearly expressions are presented first. The first expression, the initial value (α_0), is presented in an aggregated form using a monthly time step and may be calculated for each month of the hydrological year or a complete year. The α_0 is usually calculated for the year i in an annual basis as follows:

$$\alpha_0^{(i)} = \frac{\sum_{j=1}^{12} P_{ij}}{\sum_{j=1}^{12} PET_{ij}} \quad i = 1 \text{ to } N, \text{and } j = 1 \text{ to } 12 \qquad \ldots\ldots\ldots\ldots\ldots (5)$$

In which P_{ij} and PET_{ij} are the precipitation and potential evapotranspiration of the month j of the year i.

A second expression, the Normalized RDI, (RDI_n) is computed using the following equation for each year, in which it is evident that the parameter $\overline{\alpha_0}$ is the arithmetic mean of α_0 values calculated for the N years of data.

$$RDI_n^{(i)} = \frac{\alpha_0^{(i)}}{\overline{\alpha_0}} - 1 \qquad \ldots\ldots\ldots\ldots\ldots (6)$$

The third expression, the Standardized RDI (RDI_{st}), is computed following similar procedure to the one that is used for the calculation of the SPI. The expression for the Standardized RDI is:

$$RDI_{st}^{(i)} = \frac{y^{(i)} - \bar{y}}{\widehat{\alpha_y}} \qquad \ldots\ldots\ldots\ldots\ldots (7)$$

In which $y^{(i)}$ is the ln $\alpha_{0(i)}$, $\bar{y}$ is its arithmetic mean and $\widehat{\alpha_y}$ is its standard deviation.

4.1.6 Effective drought index (EDI)

Effective drought Index (EDI) (Byun and Wilhite, 1999) in its original form used daily rainfall data to analyse drought severity and duration. It is a function of the rainfall needed for return to normal (R_n) condition, signifying the precipitation necessary for recovery from accumulated deficit since the beginning of the drought. The original and proposed forms used to analyse the monthly data for EDI computation are discussed below.

The first step is to calculate effective rainfall (R_e), defined as a function of summed values of daily precipitation with a time-dependent reduction function. Similarly, in the case of a monthly time step, it is defined as the current month's rainfall and weighted rainfall over a defined preceding period. Equation (8) is applied to compute daily depletion of water resources for the study area:

$$R_{ei} = \sum_{n=1}^{i}\left[\left(\sum_{m=1}^{n} P_m\right)/n\right] \qquad \text{...} \qquad (8)$$

Where i is the summation duration (SD; dry duration added to 365 on D-day), P_m is the daily precipitation of m days before, and n is the number of days whose precipitation data are averaged for. $(R_e)_i$ is derived from the concept that precipitation m days before is added in the form of average precipitation from (day1) to (day n).

The precipitation needed for return to normal $(R_{n)j}$ is computed as given below. Negative values of deviation in rainfall (R_d), = [$(R_e$-$R_m)$, where R_m is the mean of R_e, can be calculated directly to convert it to the 1-day precipitation needed for a return to normal condition $(R_n)_j$ as below:

$$Rn_j = \frac{Rd_j}{\sum_{n=1}^{j}(1/n)} \qquad \text{..} \qquad (9)$$

Where j is the total duration in days (i.e. the number of days over which precipitation deficit is accumulated) and n D 1, 2, 3, 4. . . j. For example, R_n400 shows the precipitation needed for recovery from the deficit accumulated during the last 400 days, in which daily depletion of water resources is taken into account. R_n365 is a little more important: if R_n365 is positive, then all other drought indices are not calculated despite the accumulated water deficit. Average precipitation deficit (APD) and R_n are superior to EDI in the description of drought intensity. Since APD and PRN depend on the background climatology, EDI is often needed for universal drought assessment. It is expressed as

$$EDI_j = \frac{Rn_j}{Std(Rn_j)} \qquad \text{..} \qquad (10)$$

Where Std R_{nj} is the standard deviation of R_{nj} for the j^{th} month over the period of record. In monthly analysis, the first step is to calculate the effective precipitation R_e, which is defined as a function of current month's rainfall and weighted rainfall over a defined period preceding up to 48 months. For example, if Pm is the rainfall of (m = 1) months before the current month and the duration is 3, then R_e =P1 + (P1+P2)/2 + (P1+P2+P3)/3. The mean and standard deviations of R_e values for each month are then calculated and the time-series of R_e values is converted to deviations from the mean (R_d) and R_n values are calculated. The summation term is the sum of the reciprocals of all the months in the duration (i.e. for 3 months: 1/1+1/2+1/3). Finally, EDI is calculated, as in the above daily case, where Std(PRN) is the standard deviation of the relevant months' PRN values. No normalization of the index or rainfall data is performed, and the skew ness of the original time-series is preserved. This means that positively skewed rainfall data can result in a larger range of positive EDI values than the range of negative EDI values. Here, it is noted that these negative values actually represent the 'rainfall' required for a return to normal from a drought. The classification of the drought severity by the Effective Drought Index is shown in Table 3.Or some researchers also classified EDI as extreme drought (EDI ≤ -2), severe drought (-2≤EDI≤-1.5), moderate drought (-1.5≤EDI≤-1.0), near normal (-1.0≤EDI≤1.0).

Table 3: The classification of the drought severity by the Effective Drought Index

	In spring Season	In rainy Season	Other Season
Moderate Drought	-0.5 >	-1.0 >	-0.7 >
Severe Drought	-1.0 >	-2.0 >	-1.5 >
Extreme Drought	-2.0 >	-3.0 >	-2.5 >

4.1.7 Aridity Index

The ratio of annual potential evaporation to precipitation, referred to as the aridity index, which is considered as a numerical indicator of the degree of dryness of the climate at certain location. UNESCO classified aridity index to different groups in the year (1979) (Table 4).

The India Meteorology Department has developed an Aridity Anomaly Index based on rainfall, potential evapotranspiration and actual evapotranspiration, taking into account soil moisture conditions and using the water budgeting method. Aridity anomalies are worked out based on this index and these anomalies are classified into various categories of arid conditions- — Mild Arid (aridity anomaly 1–25%), Moderate Arid (aridity anomaly 26–50%), and Severe Arid (aridity anomalies more than 50%). These anomalies are used for near real-time monitoring and assessment of agricultural droughts across the country at weekly/fortnightly intervals. This indirectly helps to assess the moisture stress experienced by growing plants.

Table 4: UNESCO (1979) aridity classification

Classification of Aridity index	
Hyper-arid	AI<0.03
Arid	0.03<AI<0.20
Semi-arid	0.20<AI<0.50
Dry sub-humid	0.50<AI<0.65

4.2 Hydrological data based drought analysis

4.2.1 Streamflow Drought Index (SDI)

According to Nalbantis (2008), if a time series of monthly streamflow volumes Qi,j is available, in which i denotes the hydrological year and j the month within that hydrological year (j = 1 for October and j = 12 for September), Vi,k can be obtained based on the equation:

$$V_{i,k} = \sum_{j=1}^{3k} Q_{i,j} \qquad i = 1,2, \ldots .j = 1,2, \ldots \ldots k = 1,2,3,4 \qquad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots. (11)$$

In which Vi,k is the cumulative streamflow volume for the i-th hydrological year and the k-th reference period, k = 1 for October-December, k = 2 for October-March, k = 3 for October-June, and k = 4 for October-September.

Based on the cumulative stream flow volumes Vi,k, the Stream flow Drought Index (SDI) is defined for each reference period k of the i-th hydrological year as follows:

$$SDI_{i,k} = \frac{V_{i,k} - \overline{V}_k}{s_k} \qquad i = 1,2, \ldots .k = 1,2,3,4 \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (12)$$

In which Vk and sk are respectively the mean and the standard deviation of cumulative streamflow volumes of the reference period k as these are estimated over a long period of time. In this definition the truncation level is set to Vk although other values based on rational criteria could be also used.

Generally, for small basins, streamflow may follow a skewed probability distribution which can well be approximated by the family of the gamma distribution functions. The distribution is then transformed into normal. Using the two-parameter log-normal distribution (for which the normalisation is simply reclaiming the natural logarithms of streamflow), the SDI index is defined as:

$$SDI_{i,k} = \frac{y_{i,k} - \overline{y}_k}{s_{y,k}} \qquad i = 1,2\ , \ldots \ldots .k = 1,2,3,4 \ \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (13)$$

In which $y_{i,k} = \ln(V_{i,k}), i = 1,2 \dots \dots, \ k = 1,2,3,4$ are the natural logarithms of cumulative streamflow with mean and standard deviation as these statistics are estimated over a long period of time. k yk ys,

According to Nalbantis and Tsakiris (2009) states/classes (Table 5) of hydrological drought are defined for SDI in an identical way to those used in the meteorological drought indices SPI and RDI.

Table 5: Different states of hydrological drought with SDI values

State	SDI	Drought Range
0	≥0.0	Non Drought
1	-1≤SDI<0.0	Mild Drought
2	-1.5≤SDI<-1.0	Moderate Drought
3	-2≤SDI<-1.5	Severe Drought
4	SDI<2.0	Extreme Drought

4.2.2 Surface Water Supply Index

The Surface Water Supply Index (SWSI) was developed by Shafer and Dezman (1982) to complement the Palmer Index. The SWSI is a hydrological drought index that was developed to replace the PDSI in areas where local precipitation is not the sole (or primary) source of stream flow. The Surface Water Supply Index (SWSI) integrates reservoir storage, stream flow, and two precipitation types (snow and rain) at high elevations into a single index number. SWSI was designed for mountainous locations with significant snowfall because of the delayed contribution of snowmelt runoff to surface water supplies. The SWSI is calculated based on the monthly non-exceedance probability which is determined using available historical records of reservoir storage, stream flow, precipitation, and snowpack. Using a basin-calibrated SWSI algorithm, weights are assigned to each hydrological component based on its typical contribution to the water supply.

SWSI is relatively easy to calculate and it gives a representative measure of water availability across a river basin or selected region/province. It is, however, unlikely that it could be successfully used for large regions with significant spatial hydrological variability: the weights may differ substantially from one part of the region to another. SWSI is a particularly good measure of surface water supply because it accounts for the major hydrological variables that contribute to surface water supply there (Quiring et al. 2007). Like the Palmer Index, the SWSI is centered on zero and has a range between -4.2 and +4.2. SWSI estimated as:

$$\mathrm{SWSI} = \frac{aP_{snow} + bP_{prec} + cP_{strm} + dP_{resv} - 50}{12} \quad \text{(14)}$$

Where a, b, c and d are the weights for snow, rain, streamflow and reservoir storage respectively. (a+b+c+d=1).and P_i is the probability (%) of non exceedance for the i^{th} component of water balance .Calculations are performed with monthly time step.

4.2.3 Drought Severity Index (DSI)

4.2.3.1 Estimation of Variable Threshold

In the study, it is possible to choose a threshold in a number of ways depending on the type of water deficit being studied. It represents a well-defined flow quantity, such as reservoir specific yield, percentage of mean or a percentile flow in some cases, which relies on the hydrological regime. For perennial rivers, a low threshold ranging (Q70, Q90) have been considered in the past and provided good results (Hisdal et al. 2004; Meigh et al. 2002). For intermittent and ephemeral rivers with majority of zero flows, Q70 is found to be zero. As an alternative, Kjeldsen et al. (2000) suggested Q75 of monthly flow duration curve.

A large monthly variation in river flows in the study area invoked the use of variable threshold level index used for further analysis. Flow duration curves were developed for each month using the available daily streamflow data. The number of 'zero' and 'non-zero' flow values for each month were separated from the available flow records. The percentage probability of occurrence of the former in a given month can be estimated as:

$$P_i = \frac{X_i}{N} \quad \text{(15)}$$

where Pi = probability of zero flow in the ith month, Xi = number of zero flow values in the ith month, N = total number of years of flow data for the ith month, i = an integer varying from 1 to 12. Arranging the non-zero flows of each zero-flow month in descending order to rank the highest value as 1 and the lowest as (N−Xi), the joint probability of exceedance of non-zero flows was computed for the respective months as follows:

$$\mathrm{Pnz}_{j,i} = (1 - \mathrm{P_i})\frac{\mathrm{R_{j,i}}}{\mathrm{N - X_i}} \quad \text{(16)}$$

Where Rj,i = rank of the j^{th} flow value of the i^{th} month, Pnzj,i = joint probability of exceedance of the j^{th} value of non-zero flow in the i^{th} month, i = an integer varying from 1 to 12 and j = an integer varying from 1−(N−Xi). Thus, the flow duration curve for each month was developed by plotting the probability of exceedance of non-zero flows (Pnzj,i) against the corresponding discharge values in the i^{th} month.

For perennial streams, the probability of exceedance was estimated using the Wiebill's plotting position formula:

$$Pn_{j,i} = \frac{R_{j,i}}{N+1} \times 100 \quad \text{(17)}$$

Where Pnj,i = probability of exceedance of the j^th^ value of flow in the ith month. Thus, to derive flow duration curves for determination of dependable flows at various probability levels,

To decide the threshold values, duration of drought, frequency of drought, and the magnitude of drought are the most important parameters (Clausen and Pearson 1995; Stahl and Demuth 1999; Bonacci 1993; Griffiths 1990; Zelenhasic and Salvai 1987).

4.2.3.2 Assessment of Drought Duration and Severity

Tel river in the study area is not running dry but having very low flow during summer at some of the sites. Using the available daily flows and the above threshold approach, a sequence of drought events was obtained. Each drought event was characterized by its duration (Di), deficit volume (or severity) (Si), and the time of occurrence (Ti). It has been obse4rved that the flow exceeds the threshold for a short period during the prolonged dry period, a long drought spell is divided into a number of minor drought events. Since these droughts are mutually dependent, it is necessary to describe the independent sequence of drought events using some kind of pooling (Tallaksen et al. 1997). If the 'inter-event' time $t_i$between the two droughts of duration d_i and $d_{i+1}$of severity S_i and $S_{i+1}$are, respectively, less than the predefined critical duration t_c, the mutually dependent drought events were pooled to form a drought event as (Zelenhasic and Salvai 1987):

$$d_{pool} = d_i + d_{i+1} \quad \text{………...} (18)$$

$$S_{pool} = S_i + S_{i+1} \quad \text{...……} (19)$$

Similarly, the two droughts can also be pooled if the ratio of inter-event excess-volume V_i to preceding deficit volume S_i is less than the predefined critical value pc. Since these two methods are not consistent in some cases, Madsen and Rosbjerg (1995) suggested to pool the two subsequent events using Equations 18 and 19 if (a) the inter-event time is less than or equal to a critical duration T_c and (b) the ratio of inter-event excess-volume and preceding deficit volume is less the critical ratio P_c. A modification based on inter-event time and volume criterion (IC) (Tallaksen et al. 1997) suggested

$$d_{pool} = d_i + d_{i+1} + t_i \qquad \text{.............................. (20)}$$

$$S_{pool} = S_i + S_{i+1} - V_i \qquad \text{.............................. (21)}$$

Equations 20 and 21 are used to identify the drought characteristics in this study.

4.2.4 Proposed Drought Severity Index

Since the length of rainy season in KBK district varies from 90 to 100 days and nearly 80–85% of the annual runoff occurs during this period only, a few heavy showers will suffice to produce the flow above the corresponding threshold, and therefore, most of the independent hydrological droughts will terminate in the monsoon season. Therefore, it is reasonable to assume the maximum duration of an independent drought event not to exceed one year. To come out with the proposed drought severity index (PDSI), the following procedure was used:

a) Number of drought days in each moth were obtained by arranging discharge data below threshold value (Q90)

b) The ratio of number of drought days and total number of days in that month were obtained (D_r).

c) The deficit stream flow volume was obtained using the equation

$$Q_d = \left(1 - \frac{\sum_i^n x_i}{n \times Q_{75}}\right) \times 100 \qquad \text{.............................. (22)}$$

Where, Q_d is the deficit streamflow discharge, Q_{75} is the 75% probability of exceedance of Streamflow, x_i is the sum of stream flow values for n number of days below threshold.

d) To obtain proposed drought severity index (PDSI) by multiplying D_r with Q_d.

4.3 Remote sensing data based drought analysis

4.3.1 Normalized Difference Vegetation Index

Normalized Difference Vegetation Index (NDVI) is based on the concept that vegetation vigour is an indication of water availability or lack thereof. The NDVI is a measure of the "greenness," or vigor of vegetation. It is derived based on the known radiometric properties of plants, using visible (red) and near-infrared (NIR) radiation. NDVI is defined as:

$$\mathrm{NDVI} = \frac{(\mathrm{NIR}-\mathrm{RED})}{(\mathrm{NIR}+\mathrm{RED})} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \text{(23)}$$

Where NIR and RED are the reflectance in the near infrared and red bands. NDVI is a good indicator of green biomass, leaf area index, and patterns of production because, when sunlight strikes a plant, most of the red wavelengths in the visible portion of the spectrum (400–700 nm) are absorbed by chlorophyll in the leaves, while the cell structure of leaves reflects the majority of NIR radiation (700-1100 nm). Healthy plants absorb much of the red light and reflect most NIR radiation. In general, if there is more reflected radiation in the NIR wavelengths than in the visible wavelengths, the vegetation is likely to be healthy (dense). If there is very little difference between the amount of reflected radiation in the visible and infrared wavelengths, the vegetation is probably unhealthy (sparse). However, this can also result from partially or non-vegetated surfaces. NDVI values range from−1 to +1, with values near zero indicating no green vegetation and values near +1 indicating the highest possible density of vegetation. Areas of barren rock, sand, and snow produce NDVI values of <0.1, while shrub and grassland typically produces NDVI values of 0.2–0.3, and temperate and tropical rainforests produce values in the 0.6–0.8 range. It should be noted that the interpretation of NDVI values is spatially dependent. This is because more productive ecosystems have different radiometric properties than less productive ones due to differences in climate, soil, and topography (Quiring and Ganesh 2010). Figure 4.1 indicates the NDVI ranges and its impact on vegetation.

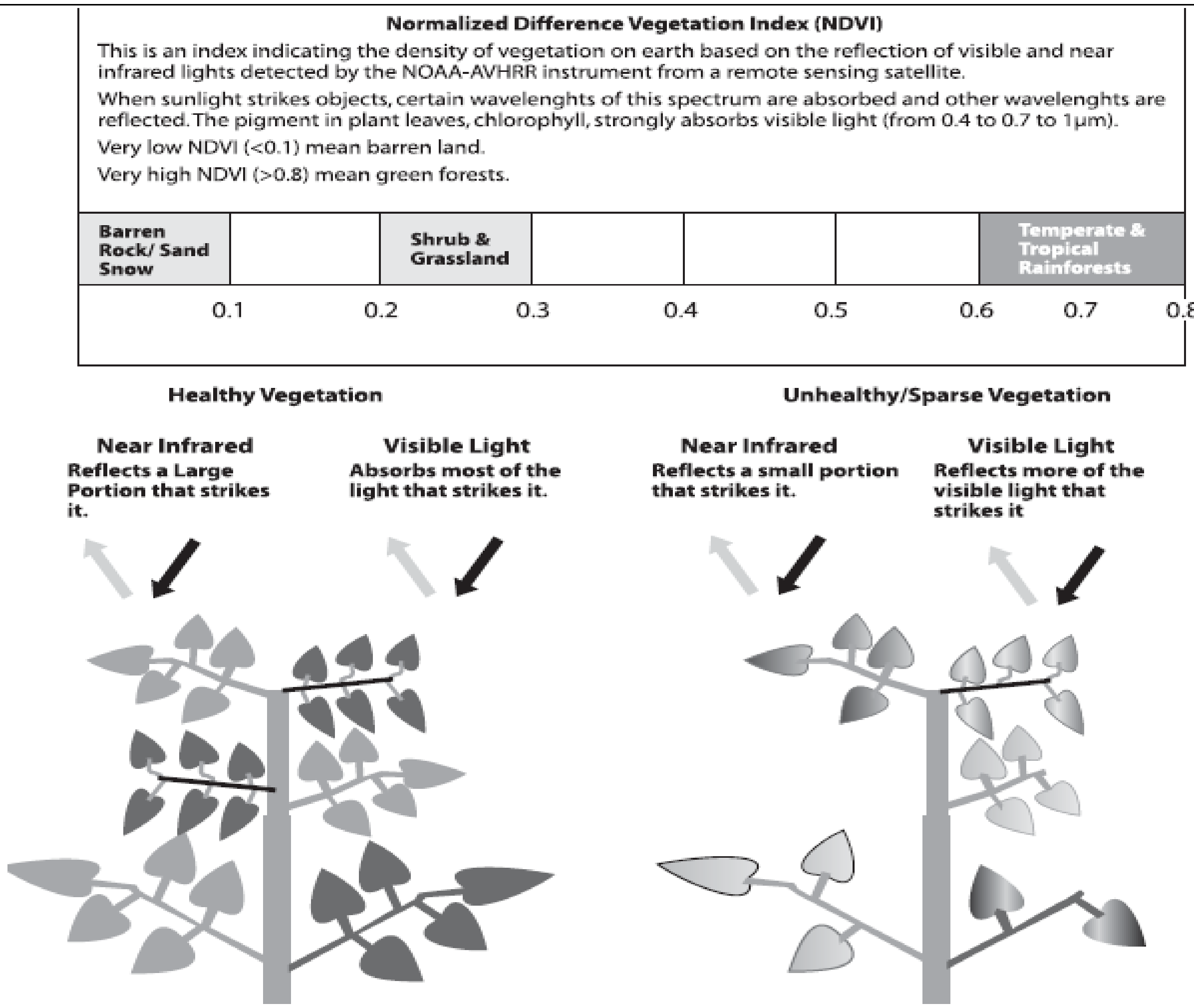

Figure 4.1: NDVI range and its impact on vegetation **(Source: Ministry of Agriculture, 2009)**

CHAPTER 5
RESULTS AND DSICUSSION

The KBK districts of the state Odisha is one of the drought prone areas of India. This area receives an average annual amount of rainfall in the order of 1100 mm and the mean potential evapotranspiration is about 2200 mm. This area had faced acute water scarcity and droughts time to time. The results of the present study had been discussed here in this chapter 5.

5.1 Meteorological data based drought analysis

5.1.1 Percentage of Departure

The computation of rainfall departure was carried out in KBK region using annual and monthly rainfall data. Annual rainfall departure (using equation 2) analysis indicated that the annual rainfall deficiency during the drought year had been varied from 38% in 1923 to 28% in 2011. It is seen from the above analysis that none of the districts were severely affected by droughts, however, maximum number of years are lying in the range of mild to moderate drought. The detail of average annual rainfall over eight stations and the marked drought years are shown in Table.1 of Appendix-II. Figure 5.1. (i): Shows the percentage departure of Nuapada district. The individual departure plots for all the districts are presented in appendix-II. From the results, it is seen that the year 2002 and 2003 are found to recent droughts in all the KBK districts.

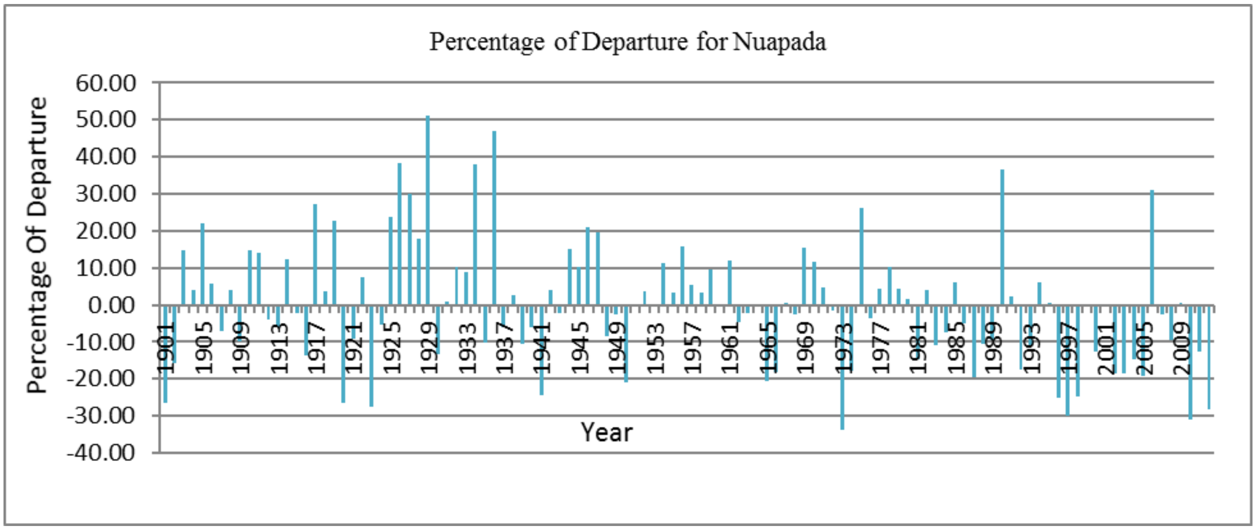

Figure: 5.1. (i): The percentage of departure Nuapada district

5.1.2 Percent of Normal

When the % of normal value decreases below 100 there is a drought situation arises so in the past decade all the eight districts suffered more or less drought. After 2000 the percent of normal values for all the eight districts were compared. The results indicating drought years in the last one decade for all the districts using equation (3) are shown in Table 5.1.2.

Table 5.1.2: Drought years obtained using Percentage of Normal method

S. No.	KBK District	Drought years
1	Balangir	2006, 2007, 2009
2	Kalahandi	2000, 2002,2003,2005,2011 2012
3	Nuapada	2000, 2001, 2002, 2003, 2004, 2005, 2007, 2008, 2010, 2011, 2012
4	Subarnapur	2000, 2001, 2002, 2003, 2004, 2010 and 2011
5	Koraput	2002, 2011
6	Malkangiri	2002, 2003, 2009, 2012
7	Nabarangapur	2000, 2002, 2003, 2005, 2011
8	Rayagada	2000.2002, 2003, 2005, 2011

The individual percent of normal plots for all the districts are presented in Appendix-III. However, the result for Nuapada is shown in Figure 5.2.(i).

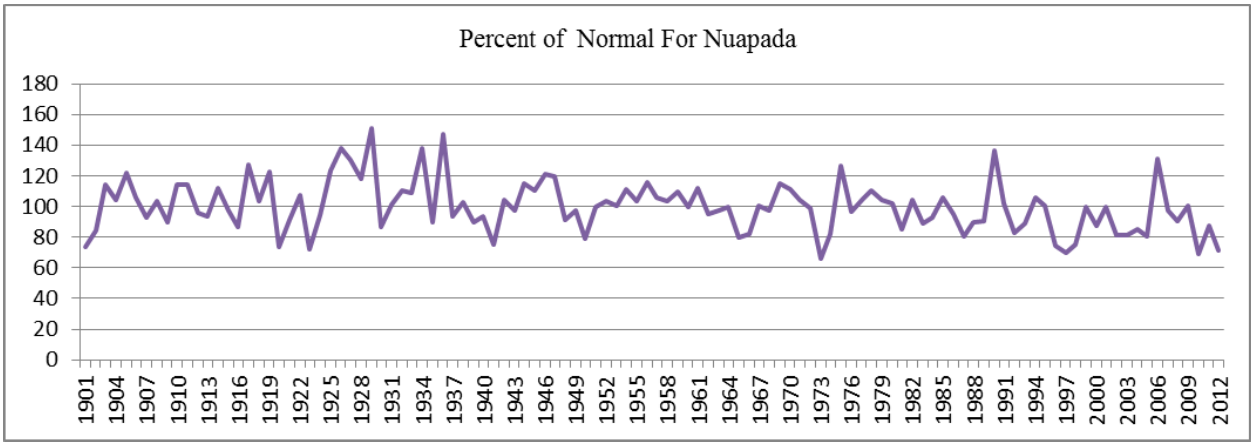

Figure: 5.2. (i): The percentage of normal plot for Nuapada district

5.1.3 Deciles

Using Table 1, the deciles were estimated for all the stations having 112 years of monthly rainfall data. It is seen that all the years are coming under the class of deciles 1-2 (20% lower), which is considered much below the normal and are drought affected years. Table 5.1.3 shows the class deciles 1-2 from the years 2000 to 2012. It has been observed that the drought is affecting Nuapada the most and Nabarangapur the least.

Table 5.1.3: Analysis of Deciles from 2000-2012

S. No	Name of Districts	Decile 1-2(20% lower)
1	Balangir	2002,2003,2004,2012
2	Kalahandi	2002,2003,2005
3	Nuapada	2002,2003,2004,2005,2010,2012
4	Sonepur	2002,2003,2004,2010,2011
5	Koraput	2002,2003,2011
6	Malkangiri	2002,2003,2009
7	Nabarangapur	2002,2003
8	Rayagada	2002,2003,2011

5.1.4 Standardized Precipitation Index (SPI)

The SPI has been applied in the study area to quantify annual precipitation deficits anomalies on annual scale for the period during 1901 to 2012.The estimate of SPI values for the time scale of 12 month has been estimated. The estimated value of SPI demarcates precipitation events over a specified time period into surplus (heavy Precipitation), medium/normal, low/deficits precipitation. The plot of SPI for 12 month time scale for all the eight districts is shown in Appendix IV. The greater value of SPI close to 1 or above indicates the wet event. The SPI value > 2 shows very heavy precipitation over the specified time scale. The SPI value between -1 to 1 shows the near normal precipitation events. Further its value -1 or less indicates drought condition. The analysis revealed that the extreme drought events with SPI values less than -2 are hardly seen. In the year 1973 Nuapada and in the years 1950, 1954 Rayagada district had this extreme kind of situation. Otherwise they all fall in the range of moderate to severe dry situation more frequently. SPI plot of Nuapadada district is shown in Figure: 5.3.(i) .and the Table 5.1.4 shows drought claimed years according to SPI in 2000-2012 for all the districts.

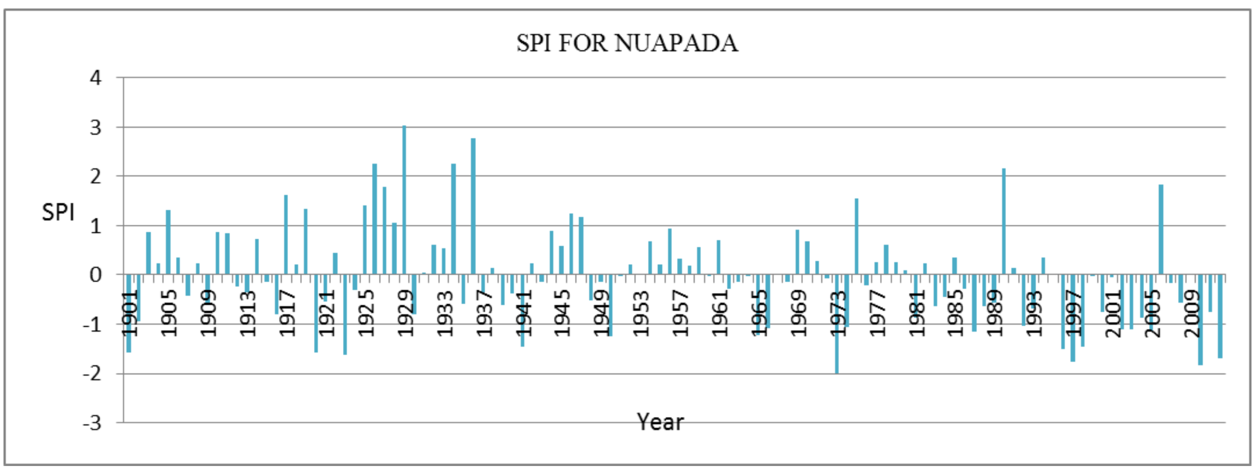

Figure: 5.3.(i): SPI plot for Nuapada district

Table 5.1.4 Analysis of SPI from 2000-2012 (Moderately affected Drought Years According to SPI Values)

S. No	Name of Districts	Drought Years
1	Balangir	2002,2003
2	Kalahandi	2002,2003
3	Nuapada	2002,2003,2005,2010,2011
4	Sonepur	2004,2010,2011
5	Koraput	2002,2003
6	Malkangiri	2002,2003
7	Nabarangapur	2002,2003
8	Rayagada	2011

5.1.5 Reconnaissance Drought Index (RDI)

The computation for RDI was carried out for drought assessment in KBK regions. Its range is similar to that of SPI. Its value -1 or less indicates dry condition.-1 to -1.49 moderately dry,-1.5 to -1.99 severely dry,-2 or less extremely dry. This study has been done for a period of 1901 to 2002. Figure 5.4 indicates the RDI values for all the districts of Odisha.From the figure 5.4 it is seen that in the year 2002 almost all districts are drought affected in the range of moderate to severe dry.

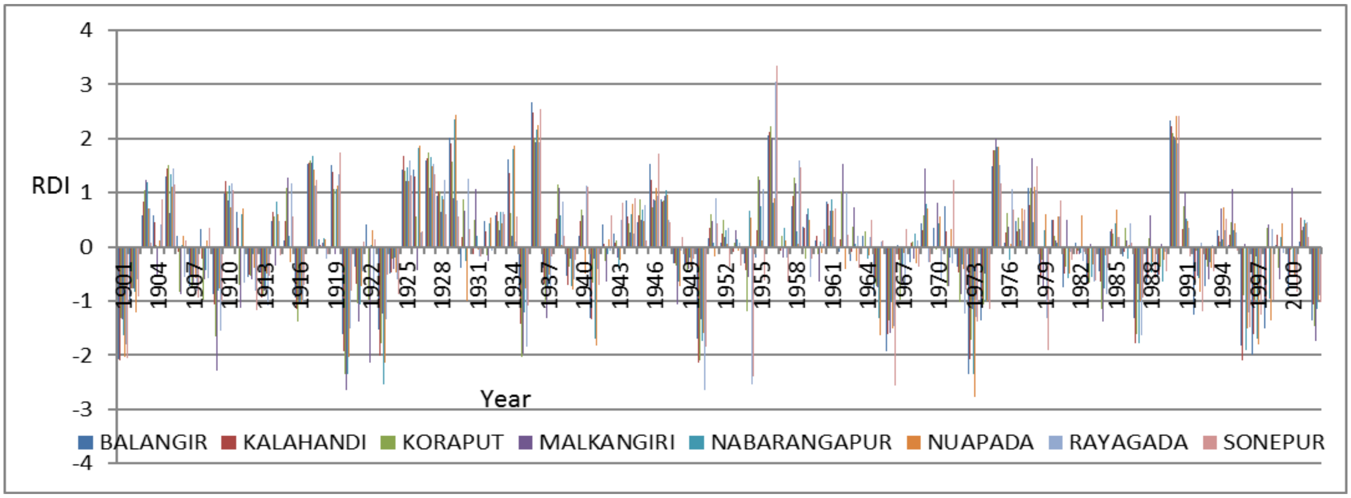

Figure 5.4: RDI for KBK districts

5.1.6 Effective drought index (EDI)

Effective drought Index (EDI) used monthly rainfall data to analyse drought severity and duration using equations 8, 9 and 10. It is a function of the rainfall needed for return to normal (R_n) condition, signifying the precipitation necessary for recovery from accumulated deficit since the beginning of the drought.

The results indicate severe drought in few years, but moderate droughts in many years. Figure 5.5. (i) Shows the EDI for the month of May for all the eight districts. EDI for the month of June and December is shown in Appendix-V. From the analysis of EDI during last one decade it is noticeably observed that, the KBK district has observed many severe droughts.

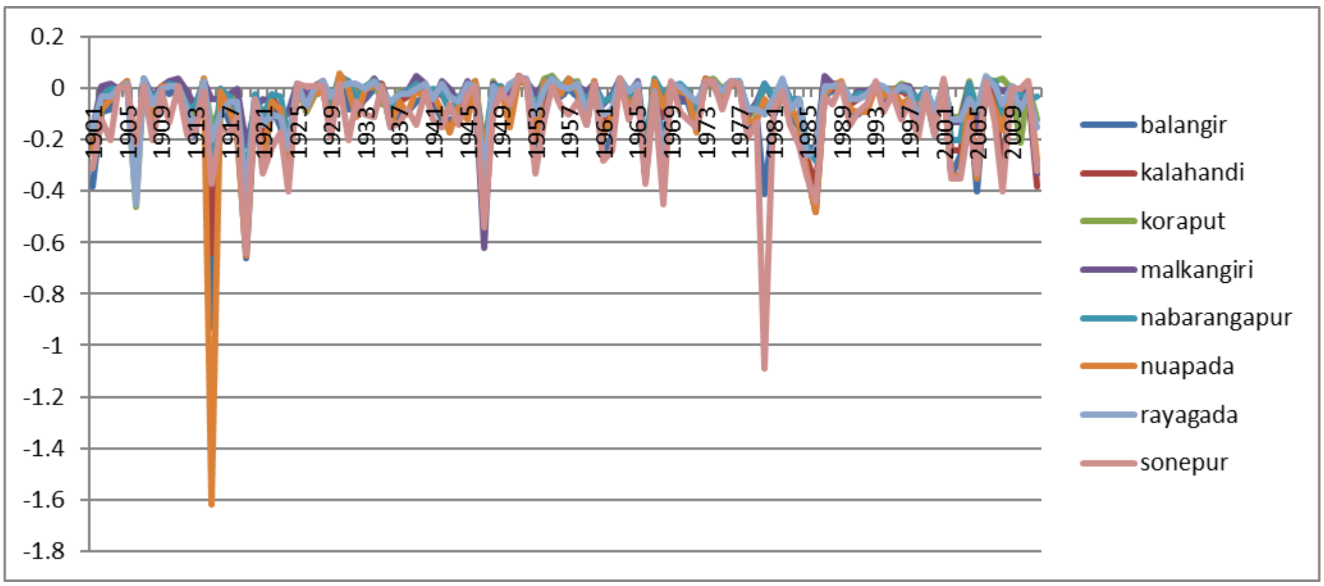

Figure 5.5. (i) EDI for all the KBK districts for the month of May

5.1.7 Aridity Index

An aridity index (AI) is a numerical indicator of the degree of dryness of the climate at a given location. The aridity index for the whole KBK region was calculated for a period of 102 year and it was found that the average value of the aridity index ranges from 0.5 to 0.6. According to the UNESCO (1979) aridity classification, if the AI varies between

0.50<AI<0.65 then it's a Dry sub-humid climate region. So the KBK region comes under sub humid climate region in India. The undivided Koraput & Balangir has an average AI of 0.57 whereas the undivided Kalahandi has an average of 0 .67. Figure 5.1.8 showing the aridity index graph for KBK districts.

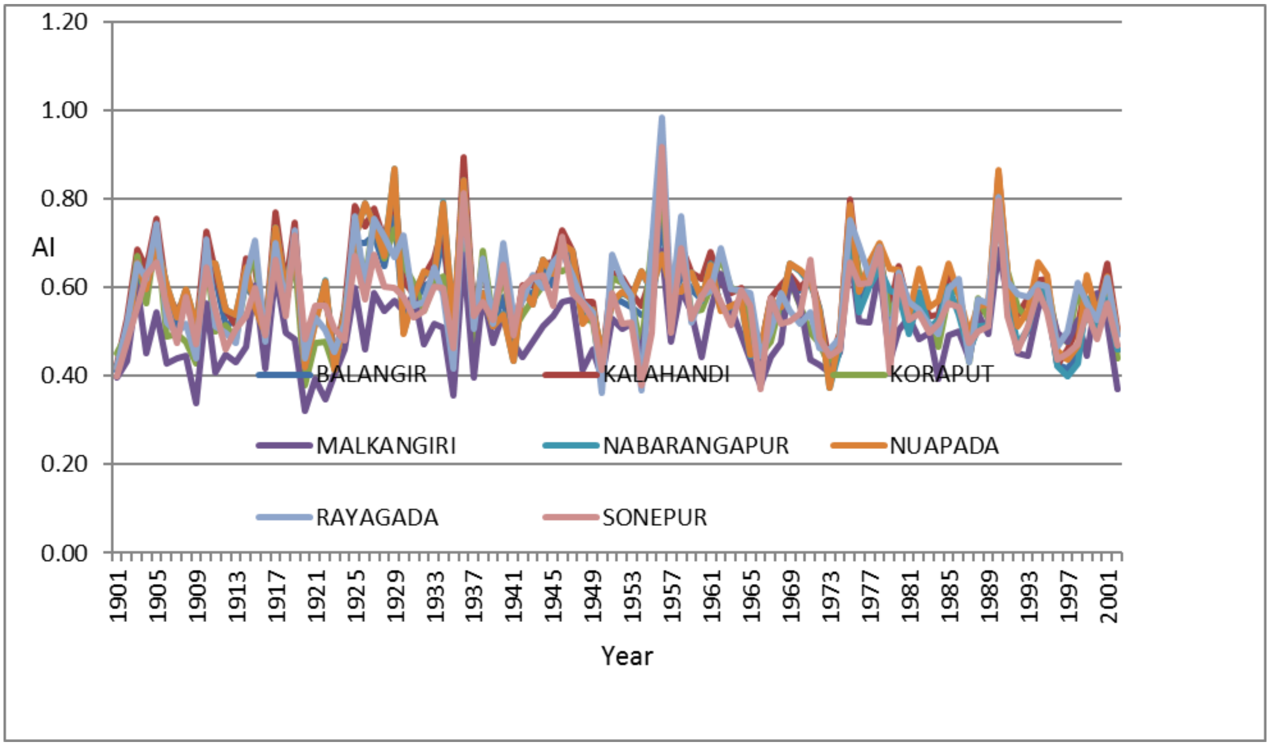

Figure 5.6 showing the aridity index graph for KBK districts.

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5.2 Hydrological data based drought analysis

5.2.1 Streamflow Drought Index (SDI)

SDI for the period of 2000-2009 is calculated for all the districts and the stream flow data was collected from different gauging stations of the study area. Majority part of the study area comes under Tel river basin, so for SDI calculation discharge data of nine stations namely Magurbeda, Kantamal, Surubali, Baragaon, Burat, Kesinga and Chitikuda of the basin is used. The basin covers mainly the Nuapada, Kalahandi, Balangir and Sonepur districts, which are more drought prone areas. Others areas of KBK districts are lying in Indravati, Kolab, and Nagavali river basins. Keeping this in view, we carried out hydrological analysis of discharge data lying in four districts only. From the analysis it is clearly seen that 2009 and 2000 are the years when maximum number of stations are witnessed the drought situation according to SDI values.

SDI value is -1.02 (-100%) lowest ever for the station Bisipada among other stations in the year 2009 resulting moderate drought. However all the stations were under the zone of mild drought situation.

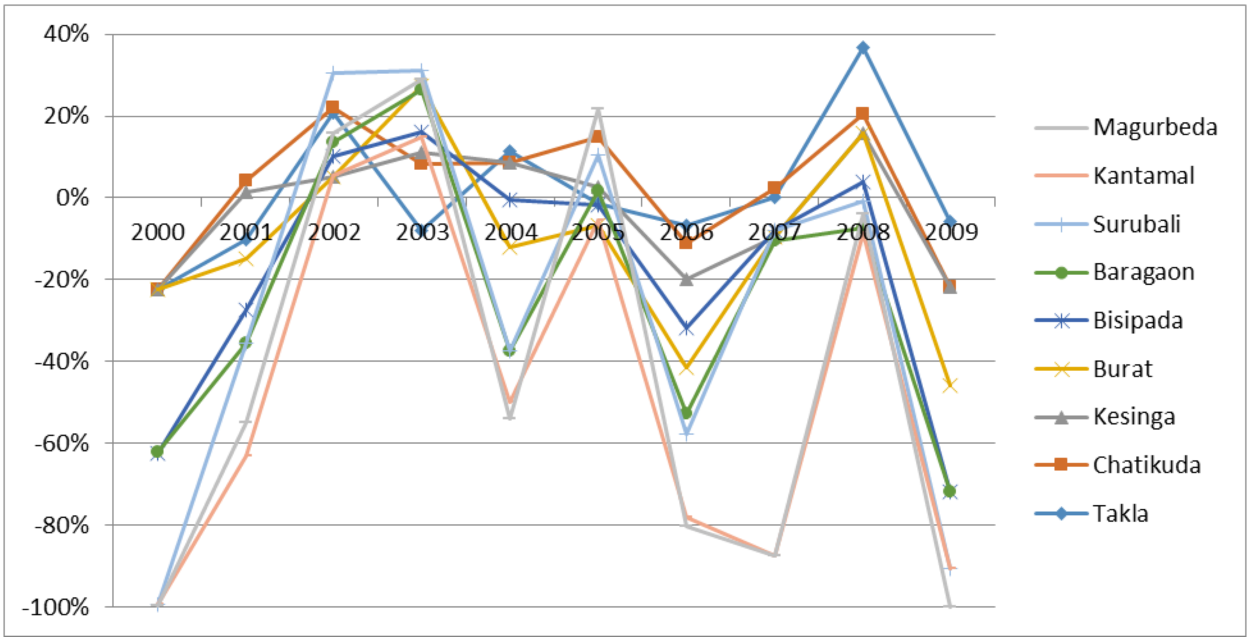


Figure5.7: SDI values for different stations from 2000 to 2009

5.2.2 Surface Water Supply Index

The SWSI is calculated based on the monthly non-exceedance probability which is determined using available historical records of reservoir storage, streamflow, precipitation, and snowpack. SWSI calculation is unique to each basin or region. In this study calculations are carried out only taking streamflow and precipitation in account equation (24) .Assigning equal weights to stream flow and precipitation.

$$\mathrm{SWSI} = \frac{bP_{prec}+cP_{strm}-50}{12} \qquad (24)$$

Where b+c=1 , P_{prec} and P_{strm} are the probability (%) of non exceedance of precipitation and streamflow respectively.

Figure 5.8 shows the SWSI for the study area basin. It is observed that Balangir,Kalahandi,Nuapada Sonepur are affected more or less in the range of moderate to severe drought from the year 2001 to 2009. It is interesting to note that rainfall is more dominating to assess the drought prone areas in comparison to discharge data.

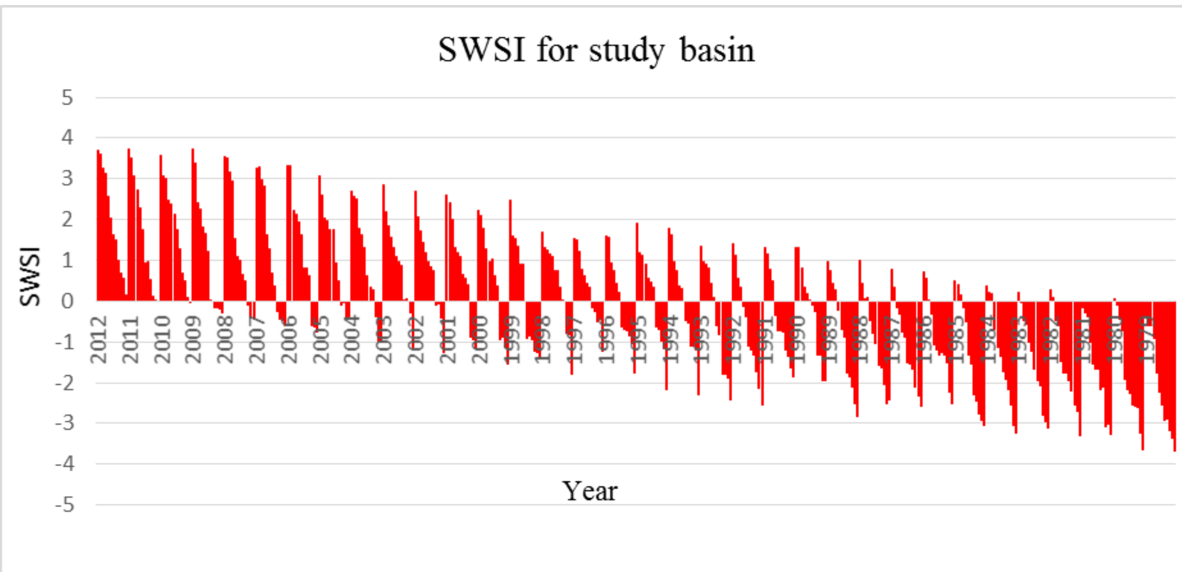
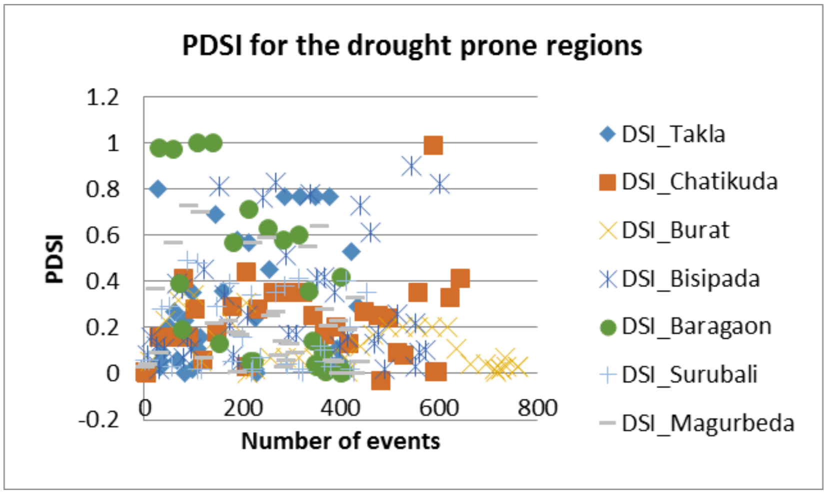


Figure 5.8: SWSI values for different years

5.2.3 Proposed Drought Severity Index

The basin covers mainly the Nuapada, Kalahandi, Balangir and Sonepur districts, which are more drought prone areas. Others areas of KBK districts are lying in Indravati, Kolab, and Nagavali river basins. Keeping this in view, we carried out hydrological analysis of discharge data lying in four districts only. As can be seen from the Figure 5.9, the drought severity is moderate to high at all the discharge sites. However, Chatikuda is receiving extremely low flows and minimum rainfall causing severe drought situation followed by Baragaon. It has been observed that the PDSI values are always above zero and have touched 0.8 on many occasions. Especially at Kesinga and Kantamal, the drought severity is more in recent past. This indicates more sever hydrological drought situation than the meteorological drought in KBK districts.



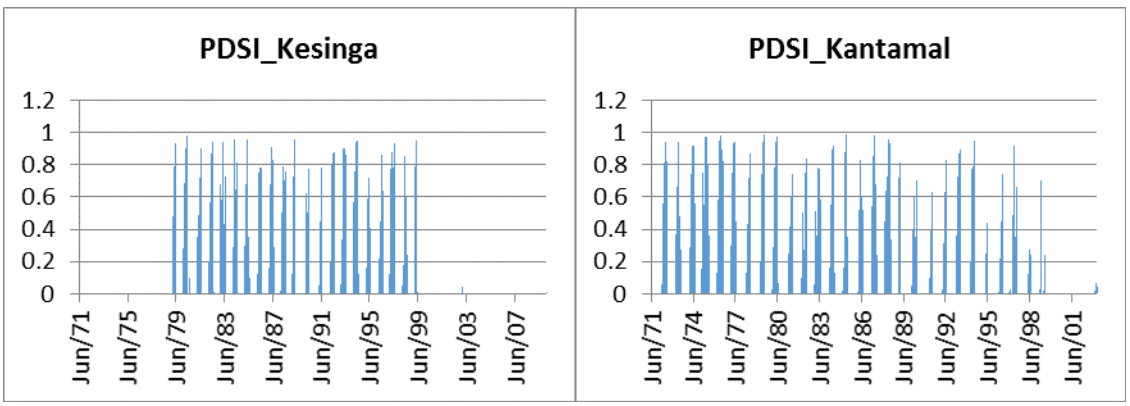


Figure 5.9-: Proposed Drought Severity Index of the study basin

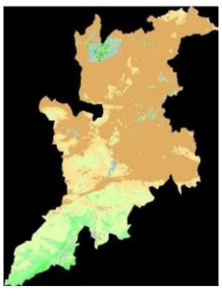
5.3: Remote Sensing Based Drought Analysis for KBK Districts of Odisha

5.3.1 Normalized Difference Vegetation Index (NDVI)

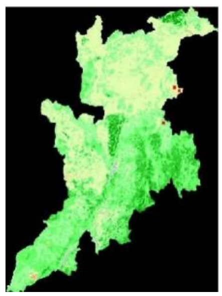
Normalized Difference Vegetation Index (NDVI) a measure of the "greenness," or vigor of vegetation. It is derived based on the known radiometric properties of plants, using visible (red) and near-infrared (NIR) radiation. NDVI images are analyzed for KBK region of different months of the year 2008 to 2010 and 2014.

Figure 5.10(i) to (xxv) shows the NDVI figures for March 2008 to March 2010. Interestingly, it has been observed that for the whole study region, the NDVI values (greenness) is reduced, which clearly substantiates the results obtained by hydrological methods further, during the year 2014, the NDVI values are very high, indicating normal and wet years.

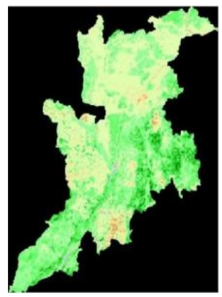
NDVI images of from March 2008 to March 2010 are analysed and it is seen that there is a severe reduce in greenness indicating severe drought condition in KBK region



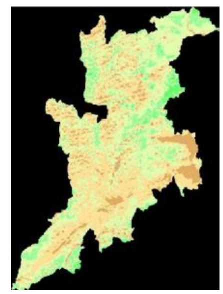
(i) March 2008



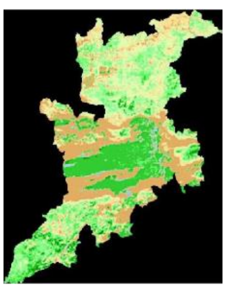
(ii) April 2008



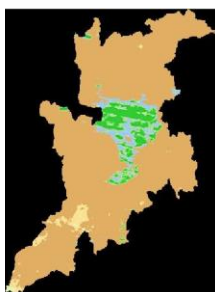
(iii) May 2008



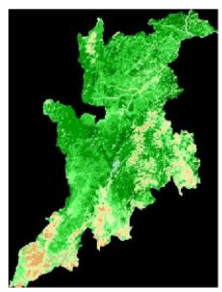
(iv) Jun 2008



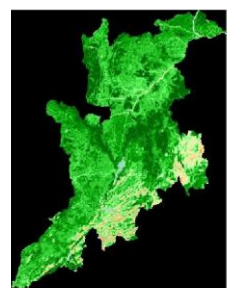
(v) July 2008



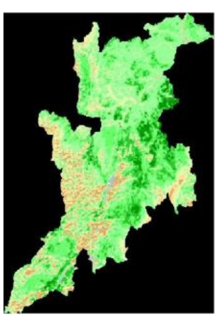
(vi) Aug 2008



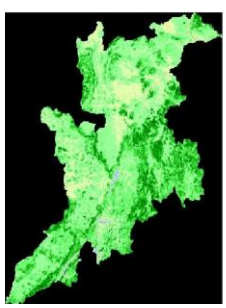
(vii) Sep. 2008



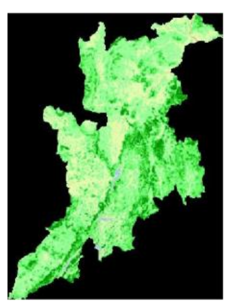
(viii) Oct 2008



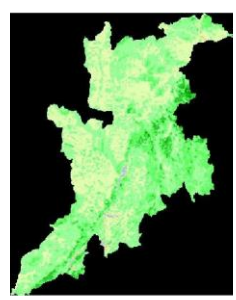
(ix) Nov 2008



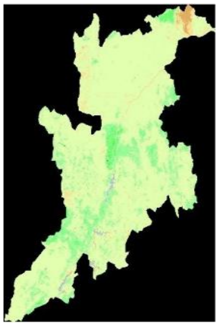
(x) Dec 2008



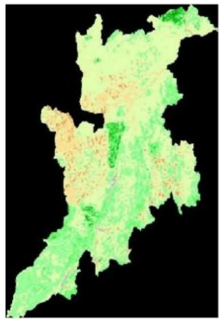
(xi) Jan 2009



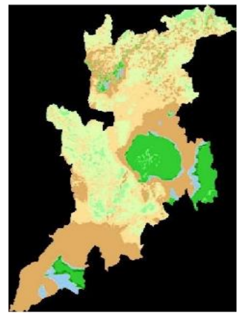
(xii) Feb 2009



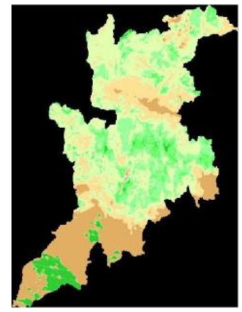
(xiii) Mar 2009



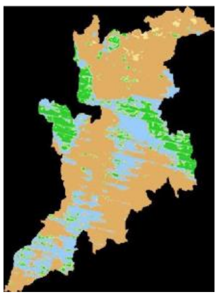
(xiv) Apr 2009



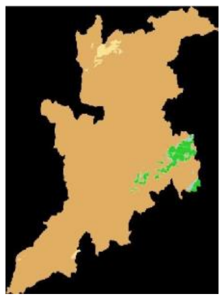
(xv) May 2009



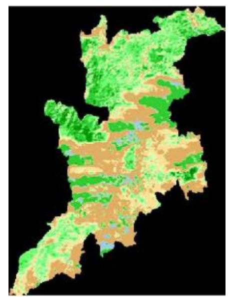
(xvi) Jun 2009



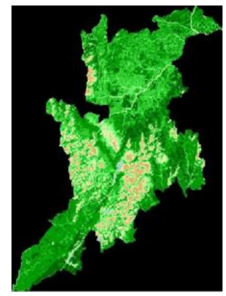
(xvii) Jul 2009



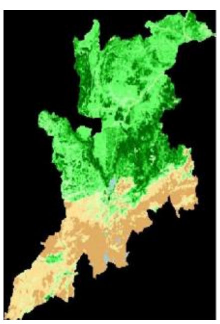
(xviii) Aug 2009



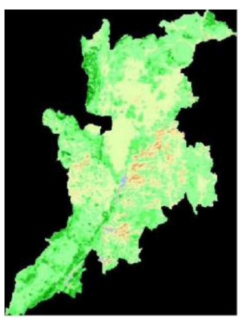
(xix) Sep 2009



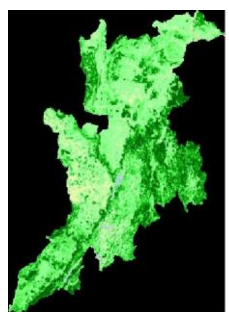
(xx) Oct 2009



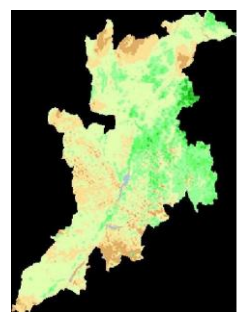
(xxi) Nov 2009



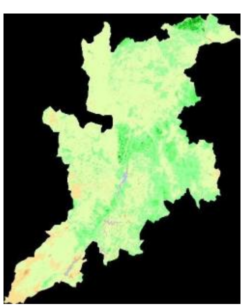
(xxii) Dec 2009



(xxiii) Jan 2010



(xxiv) Feb 2010

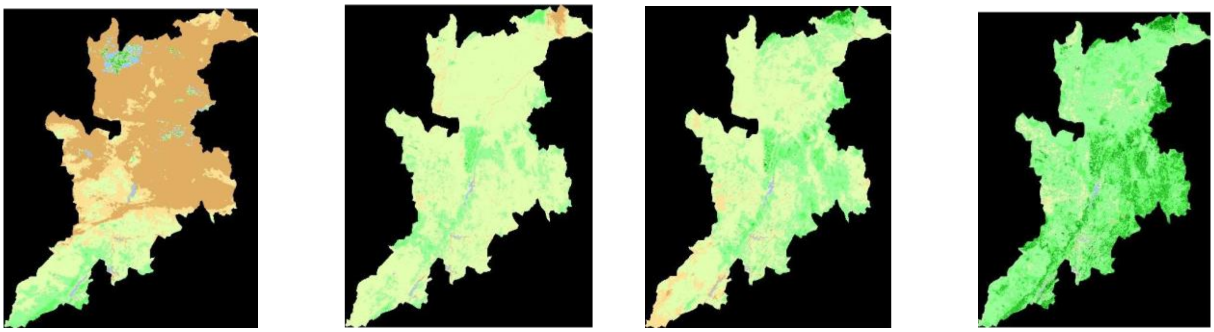


(xxv) Mar 2010

(xxv): Legend for NDVI images interpretation.

Figure: 5.10 (i) to (xxv) shows NDVI images of KBK region with legend

Again comparing NDVI images, shown in Figure 5.11 (i) to (iv) of the month of March of 2008, 2009, 2010 and 2014 we can clearly visualize the difference in greenness.



(i) Mar, 08 **(ii) Mar, 09** **(iii) Mar, 10** **(iv) Mar, 14**

Figure 5.11 (i) to (iv) Shows the NDVI images of the month March for 2008-10 and 2014

It has also been observed that Nuapada is affected by drought in most of the years, whereas Kalahandi, Balangir and Sonepur are also affected. They are coming in Mahanadi river basin and receiving less rainfall in comparison to other four districts (Malkangiri, Nabarangpur, Koraput and Rayagada).

5.4 Comparison of Results Obtained From Drought Analysis by Different Indices with Actual Data

5.4.1 Comparison of Results Obtained From Different Meteorological Data Based Drought Analysis with Actual Data.

Actual data is used from “Status of Agriculture in Odisha”, Directorate of Agriculture, Odisha which indicate 2000,2010,2011,2012 were drought years with ranging from Mild to moderate drought whereas 2002 was a severe drought year and 2004,2005,2008,2009 were moisture stress years. From the Table 5.4.1 it is summarized that when we look for only severe drought according to the actual data SPI gives better result .When we look for moisture stress, mild drought to severe drought EDI or Percentage of Departure can alone give good results also we can combine both for better outcome.

It has also been observed that Nuapada is affected by drought in most of the years, whereas Kalahandi, Balangir and Sonepur are also affected. They are lying in Mahanadi river basin and receiving less rainfall in comparison to other four districts (Malkangiri, Nabarangpur, Koraput and Rayagada).

Table 5.4.1 Drought affected years resulted from Meteorological drought analysis

	PERCENTAGE OF DEP.	PERCENT OF NORMAL	DECILES	SPI	EDI	ACTUAL
Balangir	2000,2001, 2002,2003, 2004,2005, 2007,2010, 2011,2012	2006,2007, 2009	2002,2004, 2003,2012	2002,2003	2000,2002, 2003,2008, 2012	2000(MD),2002(SD),2004(MS), 2005(MS),2008(MS),2009(MS), 2010(MD),2012(MD)
kalahandi	2000,2002, 2003,2005, 2011,2012.	2000,2002, 2003,2005, 2011,2012	2002,2003, 2005	2002,2003	2000,2002, 2003,2004, 2005,2008, 2012	2000(MD),2002(SD),2004(MS), 2005(MS),2008(MS),2009(MS), 2010(MD),2012(MD)
Koraput	2000,2001, 2002,2003, 2011	2002,2011	2002,2003, 2011	2002,2003	2002,2003, 2005,2010, 2012	2000(MD),2002(SD),2004(MS), 2005(MS),2008(MS),2009(MS), 2010(MD),2012(MD)
Malkangiri	2002,2003, 2008,2009, 2012	2002,2003, 2009,2012	2002,2003, 2009	2002,2003	2000,2001, 2002,2003, 2005,2007	2000(MD),2002(SD),2004(MS), 2005(MS),2008(MS),2009(MS), 2010(MD),2012(MD)
Nabarangapur	2000,2002, 2003,2005, 2011	2000,2002, 2003,2005, 2011	2002,2003	2002,2003	2002,2003, 2008	2000(MD),2002(SD),2004(MS), 2005(MS),2008(MS),2009(MS), 2010(MD),2012(MD)
Nuapada	2000,2001, 2002,2003, 2004,2005, 2007,2008, 2010,2011, 2012	2000,2001, 2002,2003, 2004,2005, 2007,2008, 2010,2011, 2012	2002,2003, 2004,2005, 2010,2012	2002,2003, 2005,2010, 2011	2002,2003, 2005,2008, 2012	2000(MD),2002(SD),2004(MS), 2005(MS),2008(MS),2009(MS), 2010(MD),2012(MD)
Rayagada	2000,2002, 2003,2005, 2009,2011, 2012.	2000,2002, 2003,2005, 2011	2002,2003, 2011	2011	2002,2003, 2005,2012	2000(MD),2002(SD),2004(MS), 2005(MS),2008(MS),2009(MS), 2010(MD),2012(MD)
Sonepur	2000,2001, 2002,2003, 2004,2010, 2011	2000,2001, 2002,2003, 2004,2010, 2011	2002,2003, 2004,2010, 2011	2004,2010, 2011	2000,2002, 2003,2004, 2005,2007, 2008,2012	2000(MD),2002(SD),2004(MS), 2005(MS),2008(MS),2009(MS), 2010(MD),2012(MD)

MS- Moisture Stress, MD –Mild Drought, SD-Severe Drought

5.4.2 Comparison of Results Obtained From Different Hydrological Data Based Drought Analysis with Actual Data.

From the Table 5.4.2 it is concluded that PDSI gives good result alone at the same time SWSI is also good as it takes precipitation and streamflow taken into account for SWSI calculation.

Table 5.4.2 1 Drought affected year resulted from Hydrological drought analysis

	SDI	SWSI	PDSI	ACTUAL
Balangir	2000,2009	2000,2001,2002,2003, 2004,2005,2006,2007, 2008,2009	2003,2010	2000(MD,2002(SD),2004(MS),2005(MS),2008(MS), 2009(MS),2010(MD),2012(MD)
kalahandi	2000,2009	2000,2001,2002,2003, 2004,2005,2006,2007, 2008,2009	2003,2010	2000(MD,2002(SD),2004(MS),2005(MS),2008(MS), 2009(MS),2010(MD),2012(MD)
Koraput				2000(MD,2002(SD),2004(MS),2005(MS),2008(MS), 2009(MS),2010(MD),2012(MD)
Malkangiri				2000(MD,2002(SD),2004(MS),2005(MS),2008(MS), 2009(MS),2010(MD),2012(MD)
Nabarangapur				2000(MD,2002(SD),2004(MS),2005(MS),2008(MS), 2009(MS),2010(MD),2012(MD)
Nuapada	2000,2009	2000,2001,2002,2003, 2004,2005,2006,2007, 2008,2009	2003,2010	2000(MD,2002(SD),2004(MS),2005(MS),2008(MS), 2009(MS),2010(MD),2012(MD)
Rayagada				2000,2002,2004,2005,2008, 2000(MD,2002(SD),2004(MS),2005(MS),2008(MS), 2009(MS),2010(MD),2012(MD)
Sonepur	2000,2009	2000,2001,2002,2003, 2004,2005,2006,2007, 2008,2009	2003,2010	2000(MD,2002(SD),2004(MS),2005(MS),2008(MS), 2009(MS),2010(MD),2012(MD)

MS- Moisture Stress, MD –Mild Drought, SD-Severe Drought

Chapter 6
Conclusion

6.1 Conclusions

Drought has been occurring in KBK districts of Odisha for the last one century. It is essential to come out with most appropriate techniques to assess drought in a better way and map the mild, moderate and severe droughts. From the present study, the following conclusions are drawn:

1. For meteorological data based drought analysis, the SPI, EDI and RDI demonstrate the severe drought pattern and make future predictions considering monthly rainfall data. However SPI is found to be most robust and perfect method in comparison to others, as it predicts severe drought successfully.
2. Percentage of departure, percentage to normal and Deciles indicate the values of rainfall below a threshold, which includes severe droughts too. This is helpful for planner working for mild, moderate and severe droughts.
3. It has been observed that Nuapada is severely affected by the drought most of the time. However, Kalahandi, Balangir and Sonepur are also in the line of Nuapada. (upper side of KBK districts). The districts Malkangiri, Koraput, Nabarangpur and Rayagada are less affected.
4. PDSI is a new approach and is better representing the drought using hydrological data. PDSI used in the present work is an exhaustive work done to estimate the number of drought days in each month based on probability of exceedance, and estimate drought severity based on 75% dependable flow. It indicates severe hydrological droughts in the

past and better represents the drought situation in the Nuapada, Kalahandi, Balangir and Sonepur lying in Tel basin.

5. Hydrological drought is found to be more effective in predicting drought using proposed drought severity index (PDSI) approach.
6. Satellite data based NDVI analysis is the most effective technique for spatial analysis and near real time drought assessment. As shown in previous figures Nuapada, Kalahandi, Balangir and Sonepur lying in Tel basin are most affected during the year 2008-2009.
7. It is essential for the policy makers to use SPI for rainfall based drought prediction, PDSI for hydrological based drought prediction and NDVI for agricultural drought prediction. However integrated approach using SPI, PDSI and NDVI is suggested to assess the drought taking place in reality and its quantification in eight KBK districts of Odisha.
8. The present study is able to consider, meteorological, hydrological and agricultural droughts using combination of different methods. However the combination of SPI, PDSI and NDVI are found to be best combinations.

APPENDIX I: Drought and its definitions

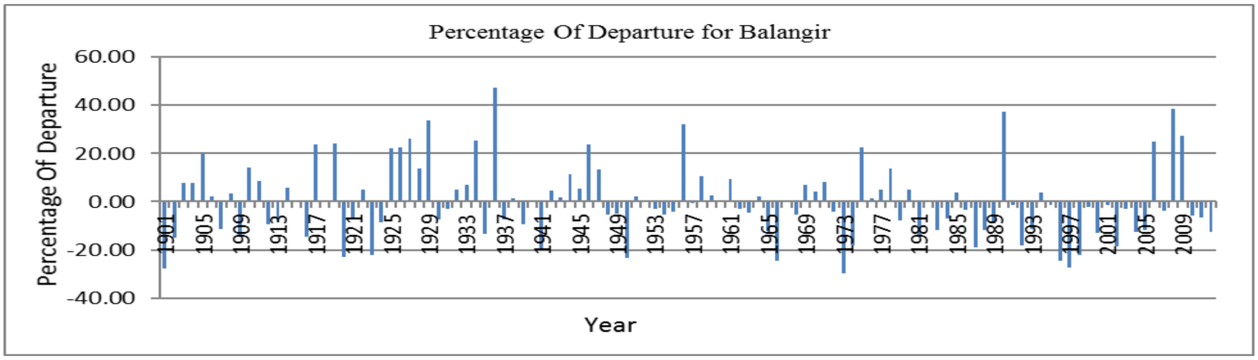
Table 1: Drought and its definitions

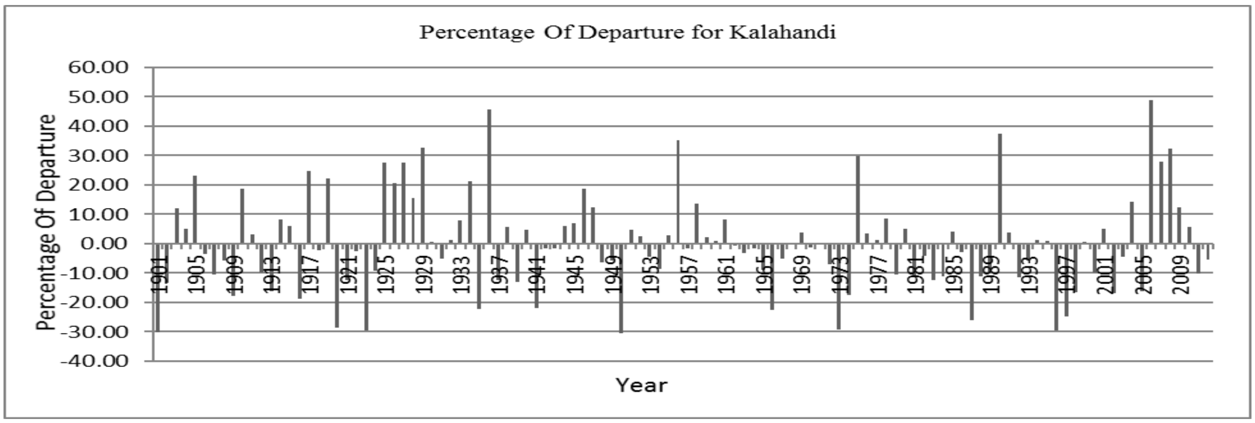
Definition	Citation
Drought as a sustained period of time without significant rainfall.	Linsely et al. (1959)
Drought as the smallest annual value of daily stream flow.	Gumbel (1963)
Drought as a significant deviation from the normal hydrologic conditions of an area.	Palmer (1965)
FAO defines a drought hazard as "the percentage of years when crops fail from the lack of moisture."	FAO (1983)
Drought means a sustained, extended deficiency in precipitation.	WMO (1986)
Drought means the naturally occurring phenomenon that exists when precipitation has been significantly below normal recorded levels, causing serious hydrological imbalances that adversely affect land resource production systems.	UN[a] Secretariat General(1994)
An extended period—a season, a year, or several years—of deficient rainfall relative to the statistical multi-year mean for a region.	Schneider (1996)
Drought is a normal part of climate, rather than a departure from normal climate.	Glantz (2003)
Drought is not a word with a precise definition. A drought is simply a period during which rainfall is markedly lower than the average for that time of year in that place, and consequently, water is in such short supply that domestic and industrial users, farmers, and wildlife are affected.	Allaby (2003)
Drought is an insidious natural hazard that results from a deficiency of precipitation from expected or "normal" that, when extended over a season or longer, is insufficient to meet the demands of human activities and the environment.	Wilhite and Buchanan-Smith(2005)

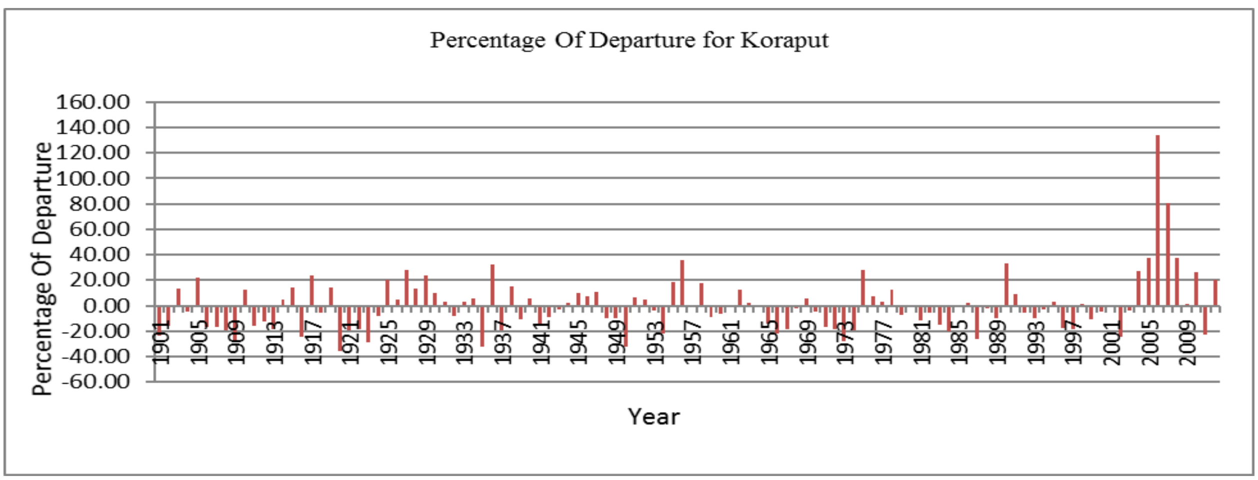
Drought is a normal, recurrent feature of climate, although often erroneously considered an unexpected and extraordinary event. It is a temporary aberration within the natural variability and can be considered an insidious hazard of nature; it differs from aridity which is a long-term, average feature of climate.	MWD (2007)
Drought is a period of drier-than-normal conditions that results in water-related problems. It is the period when rainfall is less than normal for several weeks, months or years, the flow of streams and rivers declines and water levels in lakes and reservoirs descent and the depth of water in wells increase.	Nagarajan (2009)
Drought is a recurring extreme climate event over land characterized by below-normal precipitation over a period of months to years. Drought is a temporary dry period, in contrast to the permanent aridity in arid areas.	Dai (2010)
Drought is by far the most important environmental stress in agriculture, causing important crop losses every year.	Mastrangelo et al. (2012)

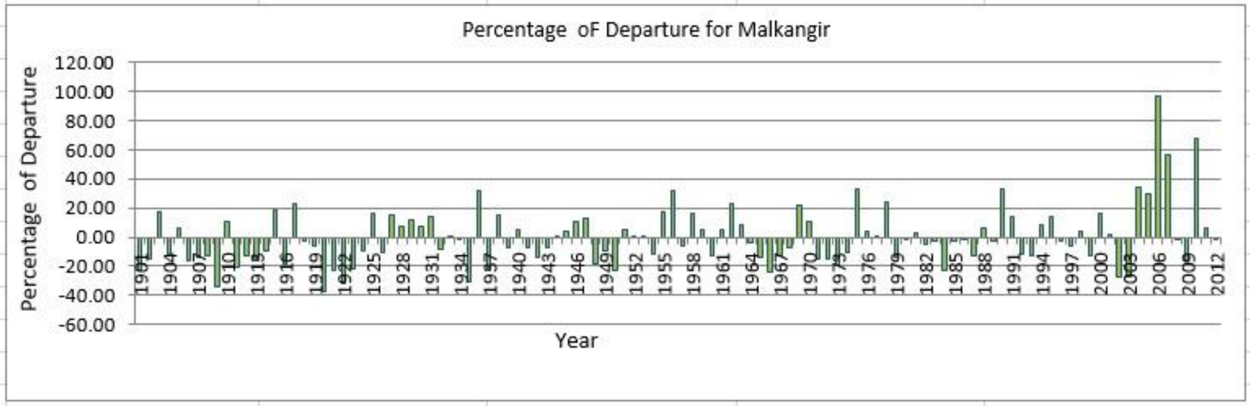
[a]UN Secretariat General, the UN Convention to Combat Drought and Desertification

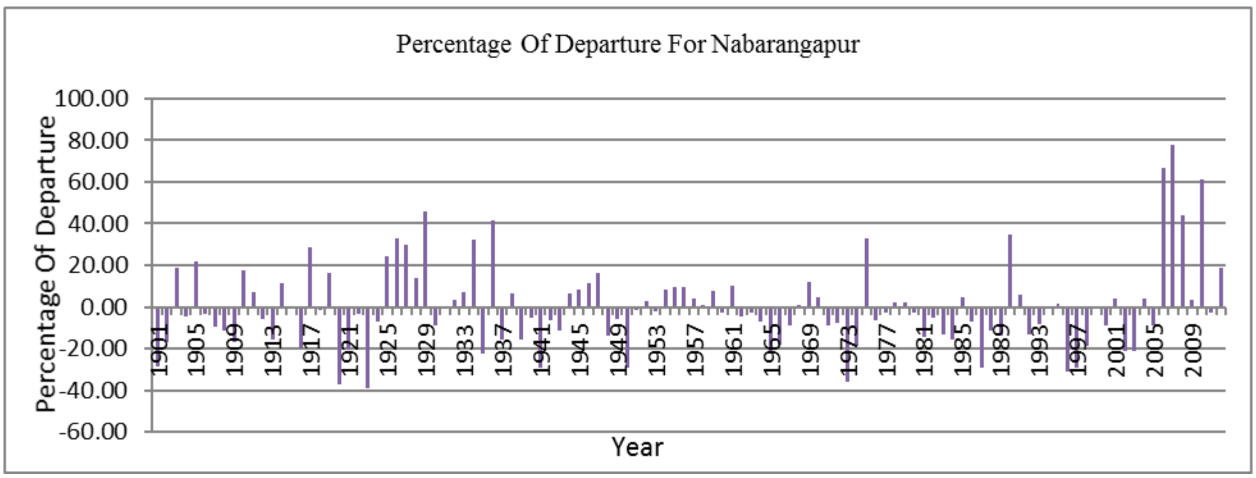
APPENDIX II: Percentage of Departure Figures For all Districts of KBK Region

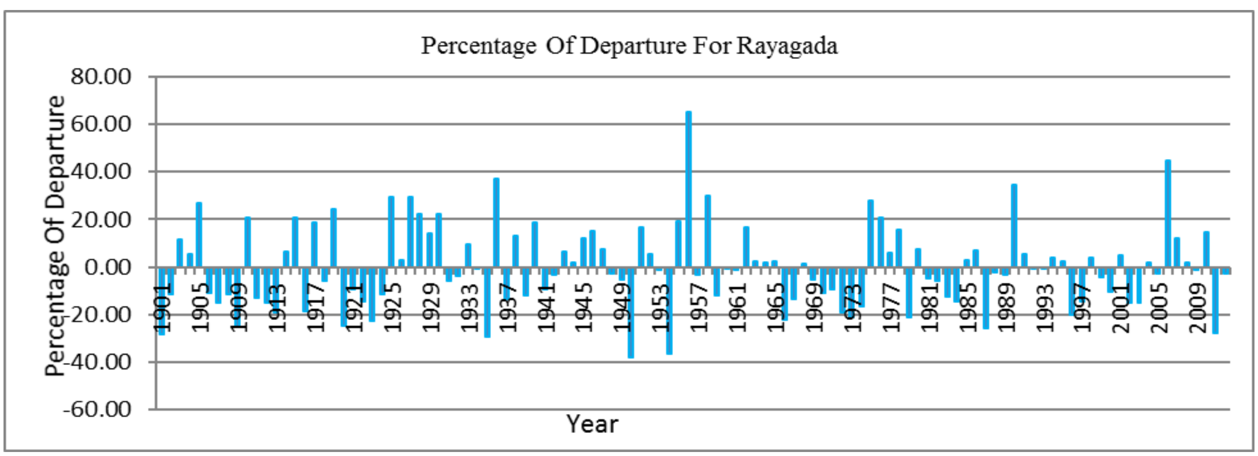


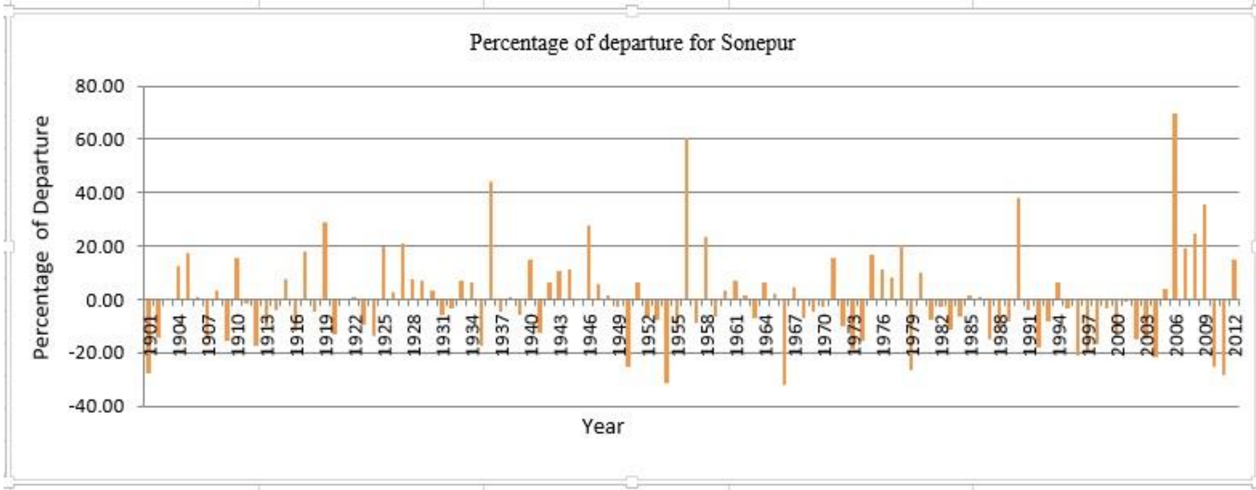





Percentage oF Departure for Malkangir
Percentage of Departure
Year


Percentage Of Departure For Nabarangapur
Percentage Of Departure
Year


Percentage Of Departure For Rayagada
Percentage Of Departure
Year



Percentage of departure for Sonepur
Percentage of Departure
80.00
60.00
40.00
20.00
0.00
-20.00
-40.00
1901
1904
1907
1910
1913
1916
1919
1922
1925
1928
1931
1934
1937
1940
1943
1946
1949
1952
1955
1958
1961
1964
1967
1970
1973
1976
1979
1982
1985
1988
1991
1994
1997
2000
2003
2006
2009
2012
Year

Table 1: Identification of different drought years in KBK districts according to Percentage of Departure.

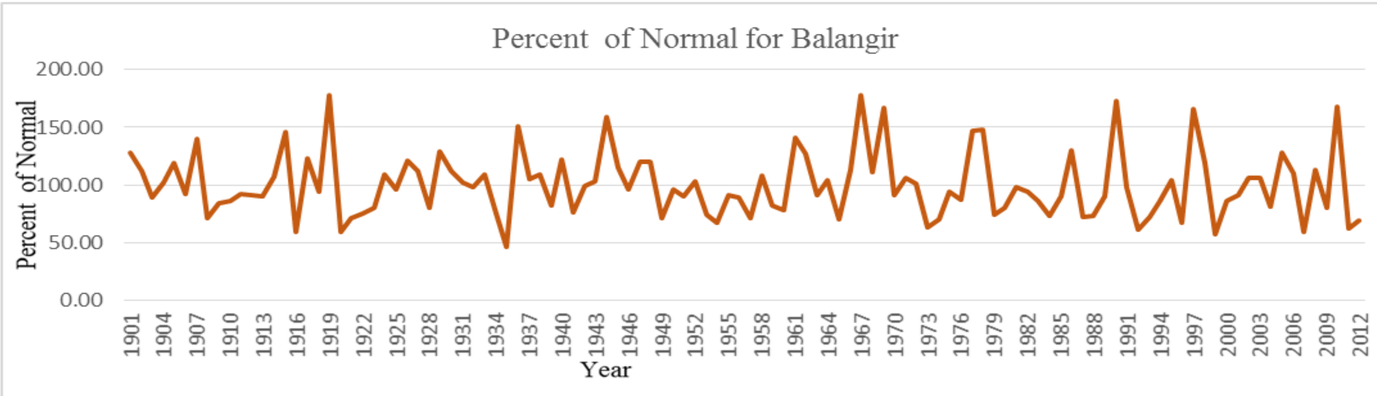
Sl. No.	District	Average Annual Rainfall(mm)	Drought Year	Maximum Annual Departure
1	Balangir	1291	1901,1902,1907,1909,1912,1913,1916,1920,21,1923,1924,1930,1931,1935,1937,1939,1941,1948,1949,1950,1953,1954,1955,1957,1962,1963,1965,1966,1967,1968,1972,1973,1974,1979,1981,1982,1983,1984,1986,1987,1989,1991,1992,1993,1995,1996,1997,1998,1999,2000,2001,2002,2003,2004,2005,2007,2010,2011,2012.	1973(-29%)
2	Kalahandi	1369	1901, 1902, 1906, 1907, 1908, 1909, 1912, 1913, 1916, 1918, 1920, 1921, 1922, 1923, 1924, 1931, 1935,1937, 1939, 1941, 1942, 1943, 1948, 1949, 1950, 1953, 1954, 1957, 1962, 1963, 1964, 1965, 1966, 1967, 1968, 1970, 1971, 1972, 1973, 1974, 1979, 1981, 1982, 1983, 1984, 1986, 1987, 1989, 1992, 1993,1996,1997,1998,2000,2002,2003,20	1950(-30%)

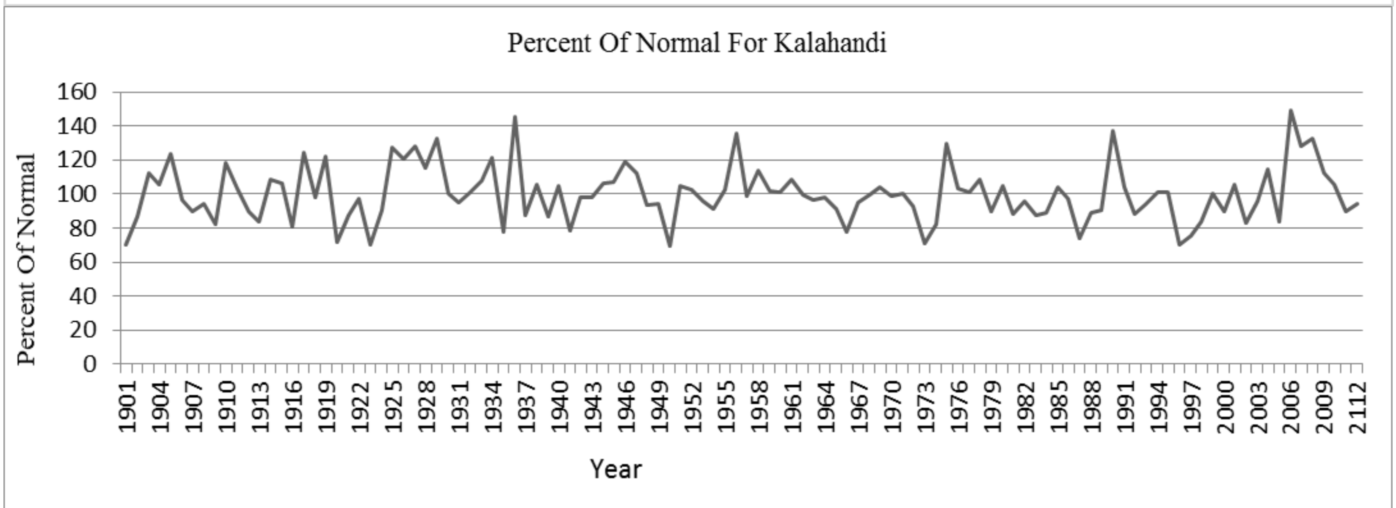
			05,2011,2012.	
3	Koraput	1297	1901, 1902, 1904, 1906, 1907, 1908, 1909, 1911, 1912, 1913, 1916, 1918, 1920, 1921, 1922, 1923, 1924, 1932, 1935, 1937, 1939, 1941, 1942, 1943, 1948, 1949, 1950, 1953, 1954, 1959, 1960, 1961, 1965, 1966, 1967, 1968, 1970, 1971, 1972, 1973, 1974, 1979, 1980, 1981, 1982, 1983, 1984, 1987, 1988, 1989, 1992, 1993, 1994, 1996, 1997, 1999,2000,2001,2002,2003,2011	1920(-35%)
4	Malkangiri	1137	1901,1902, 1904, 1906, 1907, 1908, 1909, 1911, 1912, 1913, 1914, 1916, 1918, 1919, 1920, 1921, 1922, 1923, 1924, 1926,1932, 1934, 1935, 1937,1939, 1941, 1942, 1943, 1948, 1949, 1950, 1954, 1957, 1960, 1967, 1968, 1971, 1972, 1973, 1974, 1979, 1980, 1982, 1983, 1985, 1986, 1987, 1989, 1992, 1993,1996,1997,1999,2002,2003,2008,2009,2012	1920(-37%)
5	Nabarangapur	1431	1901,1902,1904,1906,1907,1908,1909,1912,1913,1915,1916,1918,1920,1921,1922	1923(-39%)

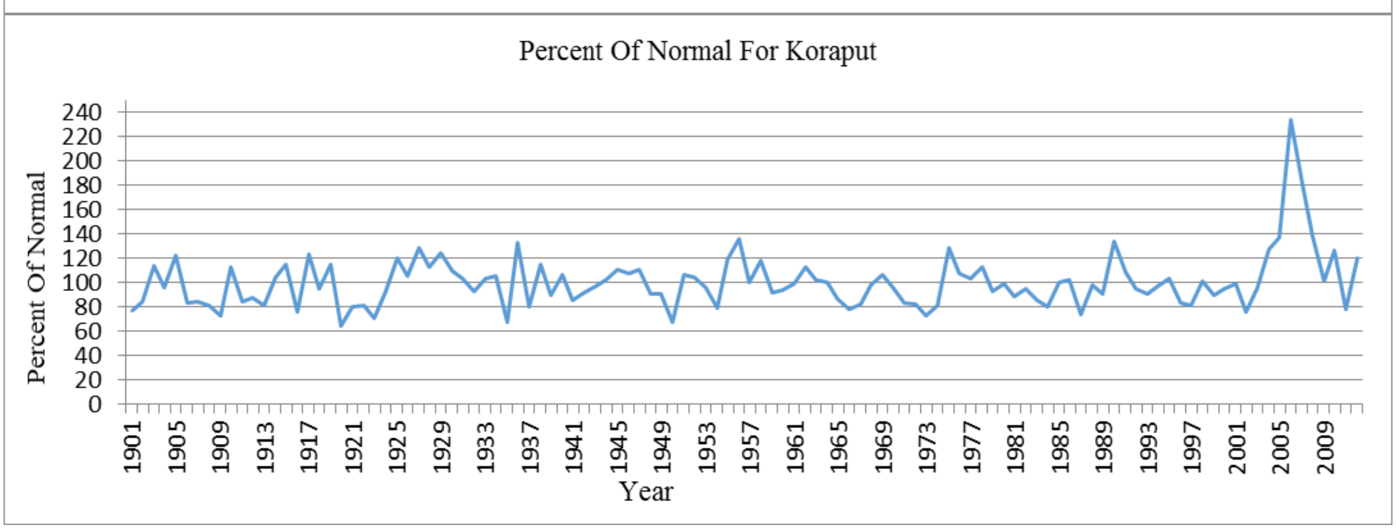
			,1923,1924,1930,1931,1935,1937,1939,1940,1941,1942,1943,1948,1949,1950,1951,1953,1960,1962, 1963,1964,1965,1966,1967,1971,1972,1973,1974,1976,1977,1980,1981,1982,1983,1984,1986,1987,1988,1989,1992,1993,1994,1996,1997,1998,1999,2000,2002,2003,2005,2011	
6	Nuapada	1306	1901,1902,1907,1909,1912,1913,1915,1916,1920,1921,1923,1924,1930,1935,1937,1939,1940,1941,1943,1948,1949,1950,1951,1960,1962,1963,1964,1965,1966,1968,1972,1973,1974,1976,1981,1983,1984, 1986,1987,1988,1989,1992,1993,1996,1997,1998,1999,2000,2001,2002,2003,2004,2005,2007,2008,2010,2011,2012	1973(-34%)
7	Rayagada	1264	1901,1902,1906,1907,1908, 1909, 1911, 1912, 1913,1916,1918,1920,1921,1922,1923,1924,1931,1932,1934,1935,1937,1939,1941,1942,1948,1949,1950,1953,1954,1957,1959,1960,1961,1966,1967,1969,1970,1971,1972,1973,1974,1979,1981,1982,1983,	1950(-38%)

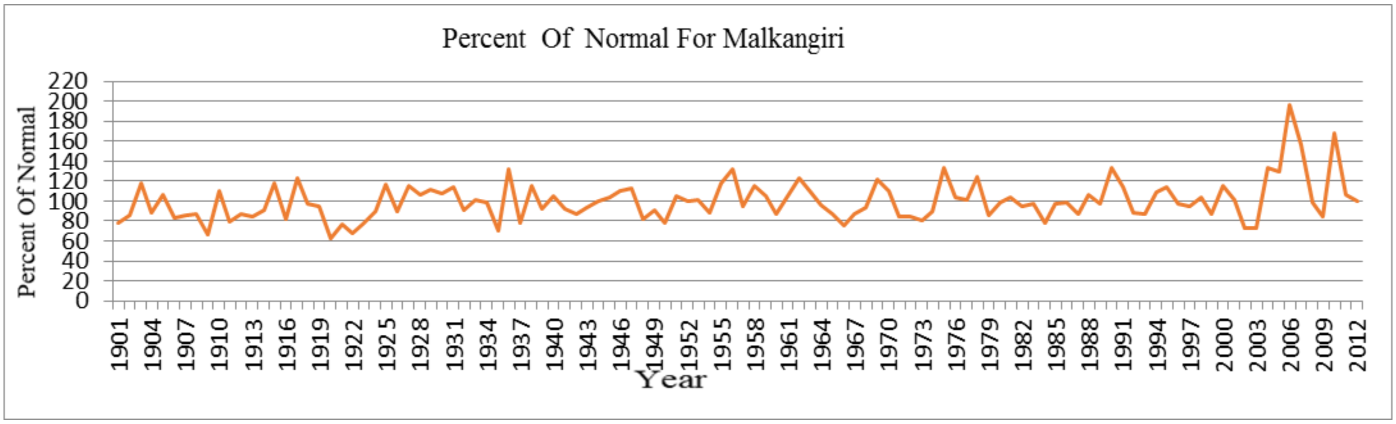
			1984,1987,1988,1989,1992,1993,1996,1997,1999,2000,2002,2003,2005,2009,2011,2012.	
8	Sonepur	1253	1901,1902,1903,1907,1909,1911,1912,1913,1914,1916,1918,1920,1921,1923,1924,1931,1932,1935,1937,1939,1941,1945,1949,1950,1952,1953,1954,1955,1957,1959,1963,1966,1968,1969,1970,1972,1973,1974,1979,1981,1982,1983,1984,1987,1988,1989,1991,1992,1993,1995,1996,1997.1998,1999,2000,2001,2002,2003,2004,2010,2011	1966(-32%)

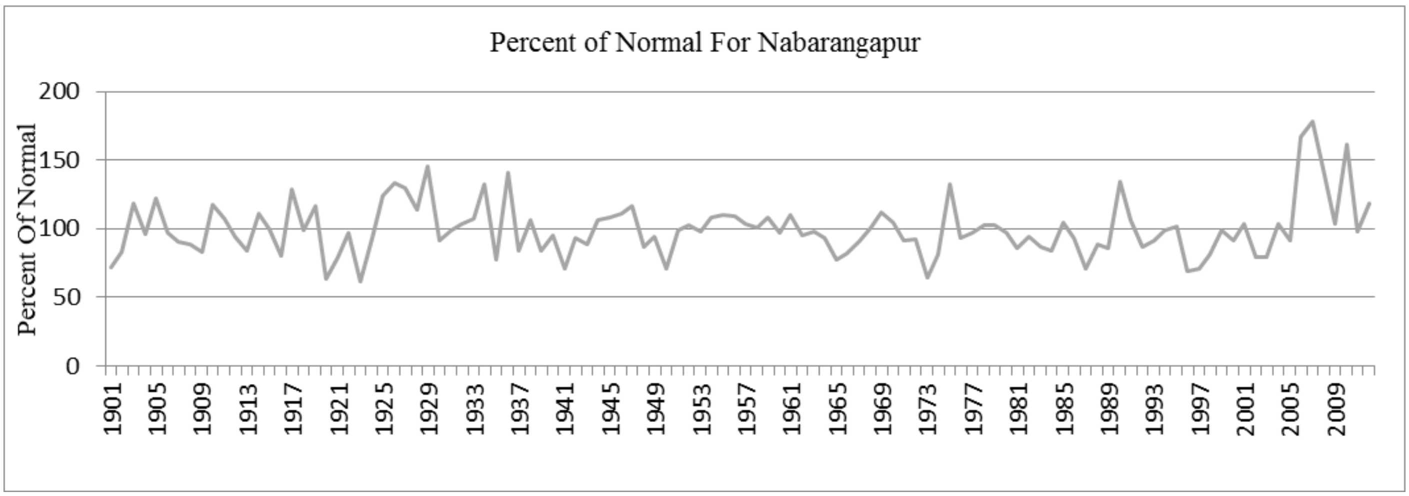
APPENDIX III: Percent of Normal Figures For all Districts of KBK Region

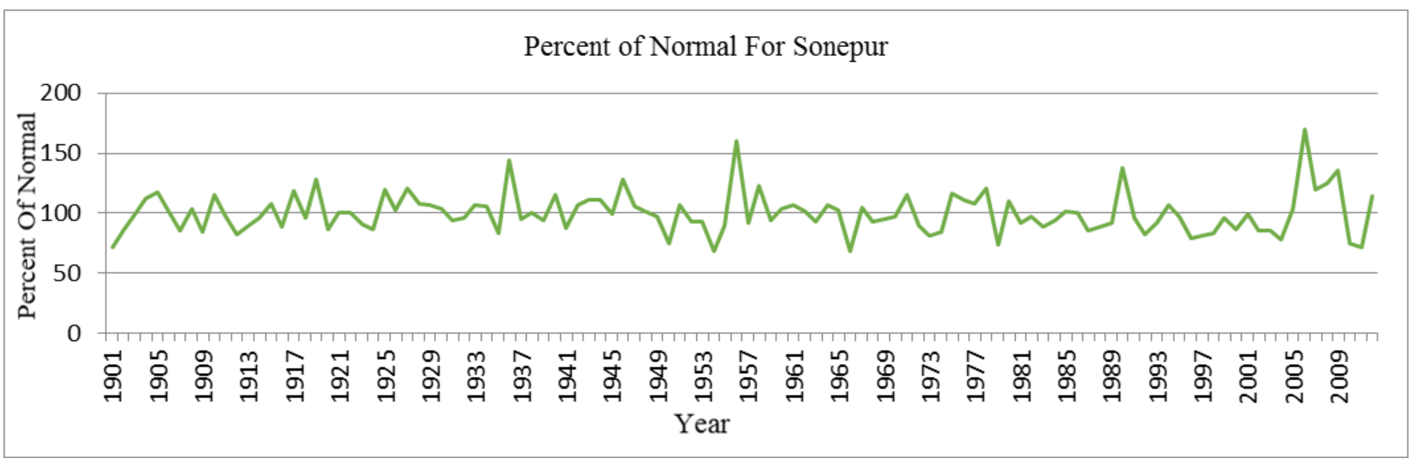




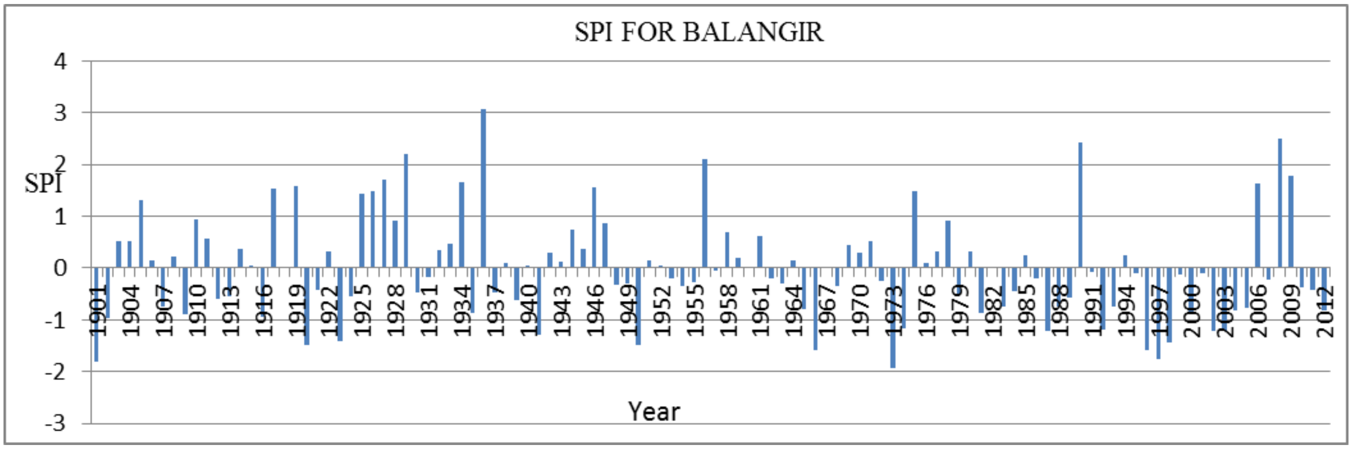


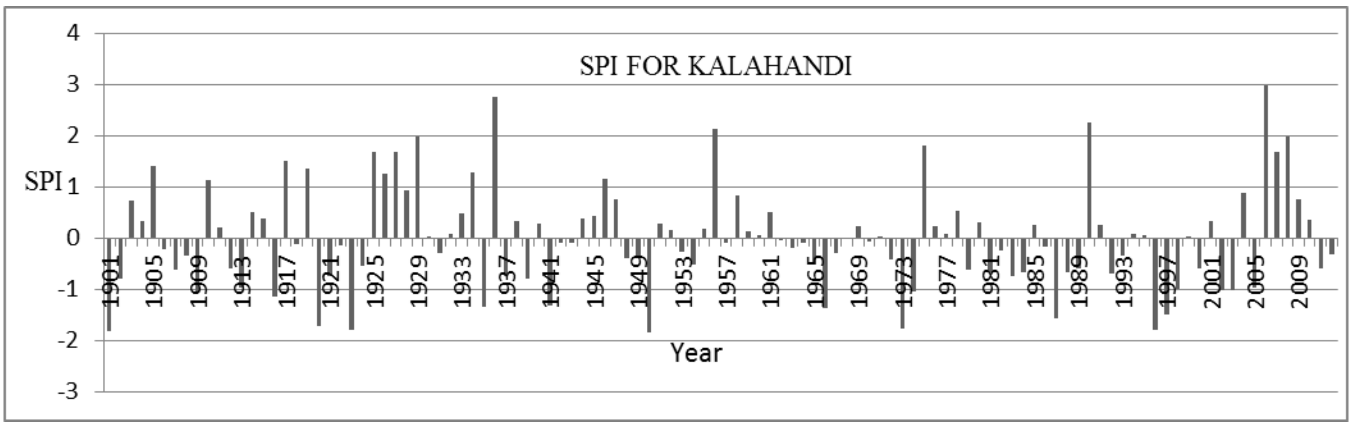

Percent Of Normal For Malkangiri
Percent Of Normal
Year

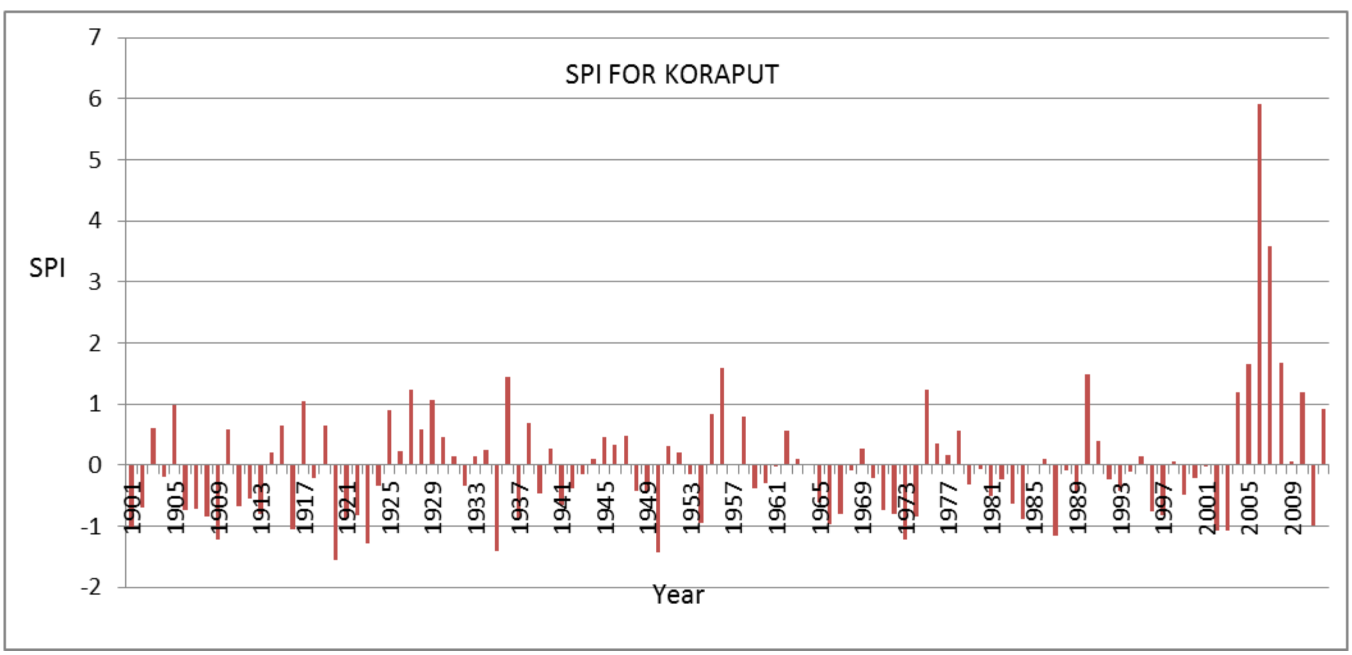

Percent of Normal For Nabarangapur
Percent Of Normal

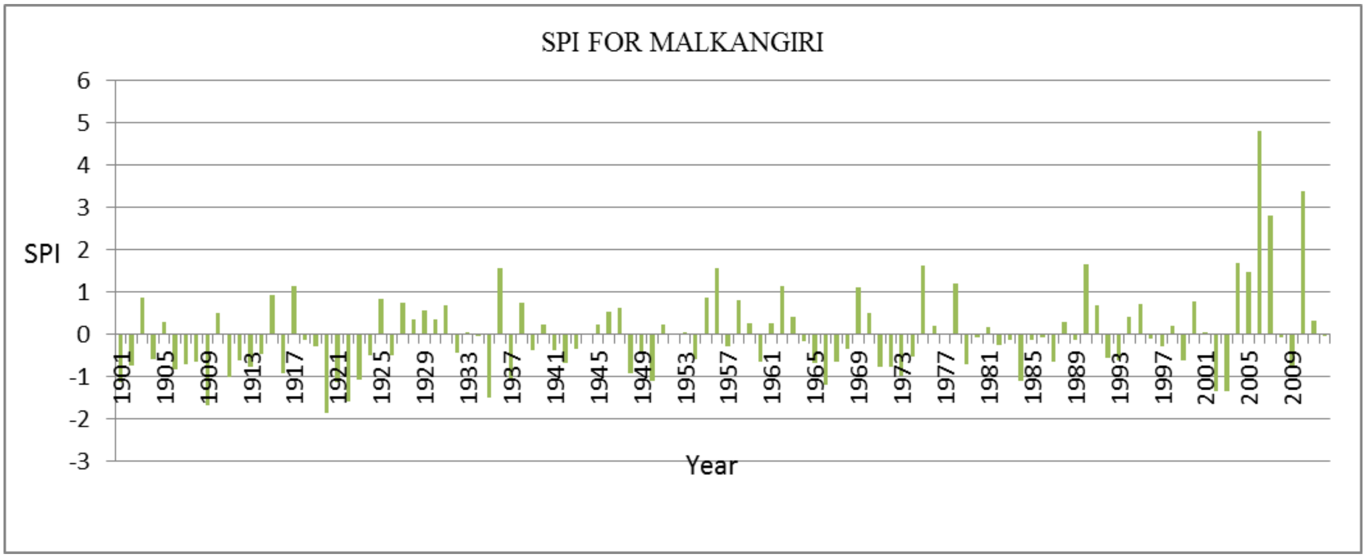

Percent of Normal For Sonepur
Percent Of Normal
Year

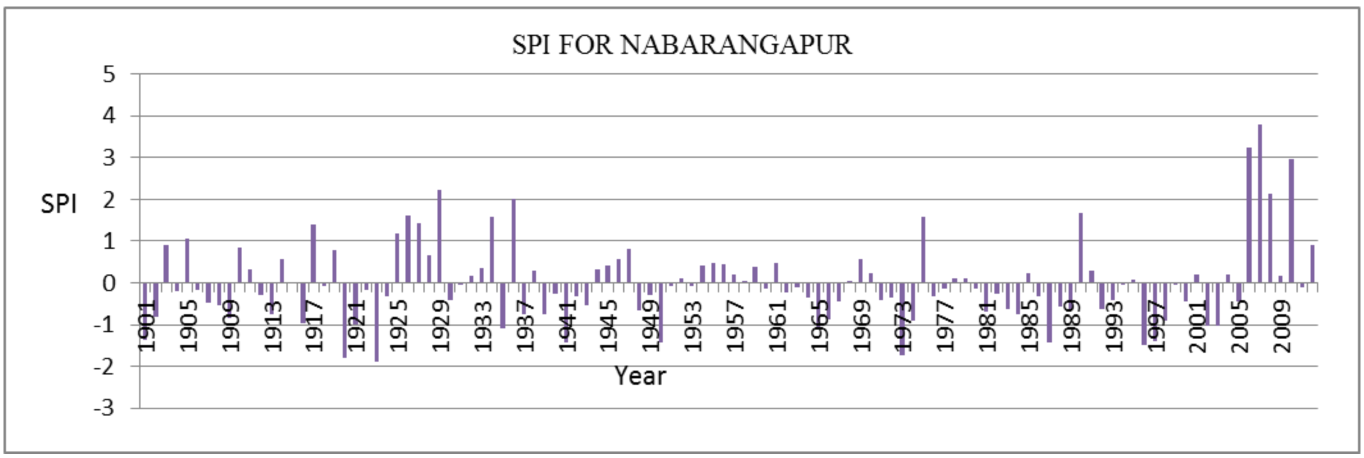
APPENDIX IV: SPI plots off all Districts of KBK region

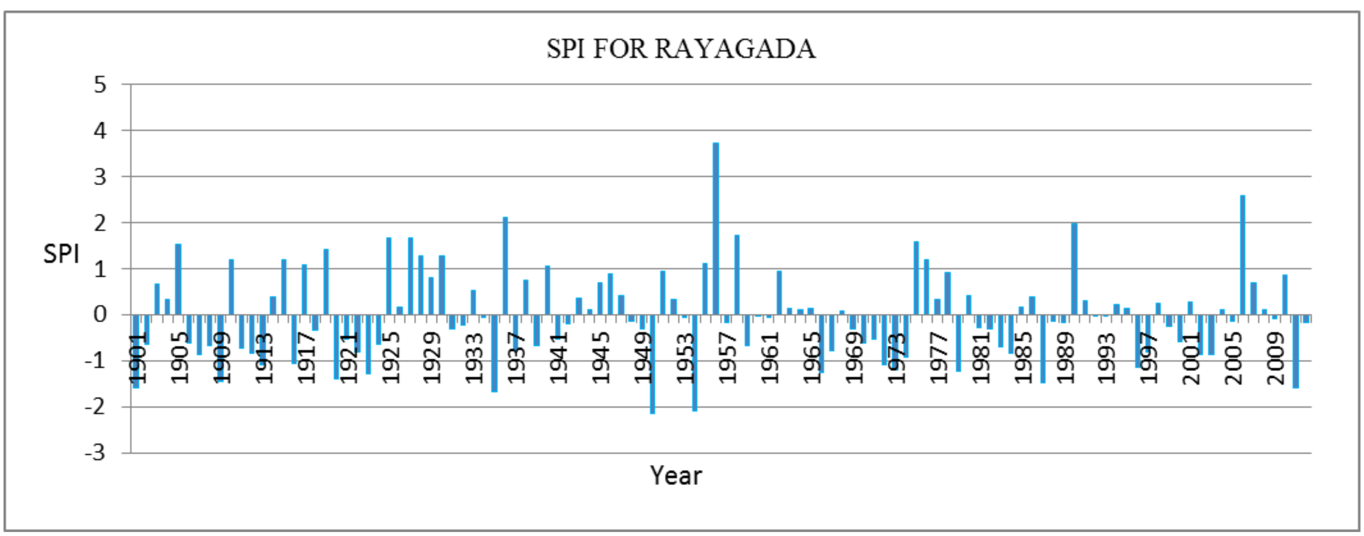


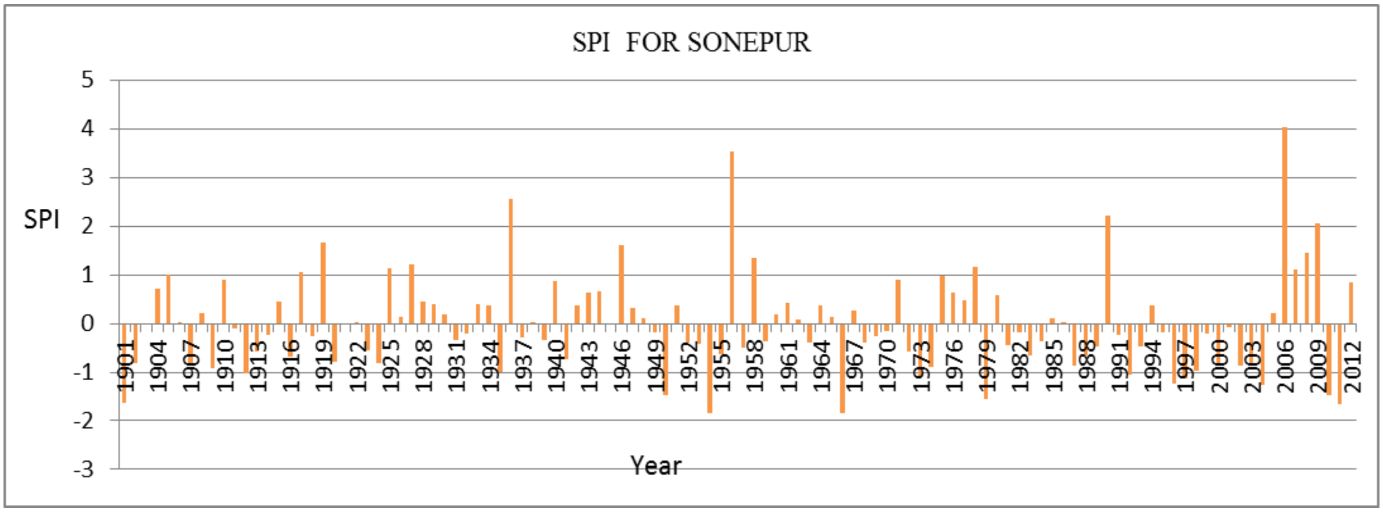





SPI FOR MALKANGIRI
SPI
Year
6
5
4
3
2
1
0
-1
-2
-3
1901
1905
1909
1913
1917
1921
1925
1929
1933
1937
1941
1945
1949
1953
1957
1961
1965
1969
1973
1977
1981
1985
1989
1993
1997
2001
2005
2009


SPI FOR NABARANGAPUR
SPI
Year
5
4
3
2
1
0
-1
-2
-3
1901
1905
1909
1913
1917
1921
1925
1929
1933
1937
1941
1945
1949
1953
1957
1961
1965
1969
1973
1977
1981
1985
1989
1993
1997
2001
2005
2009


SPI FOR RAYAGADA
SPI
Year
5
4
3
2
1
0
-1
-2
-3
1901
1905
1909
1913
1917
1921
1925
1929
1933
1937
1941
1945
1949
1953
1957
1961
1965
1969
1973
1977
1981
1985
1989
1993
1997
2001
2005
2009


SPI FOR SONEPUR
SPI
5
4
3
2
1
0
-1
-2
-3
1901
1904
1907
1910
1913
1916
1919
1922
1925
1928
1931
1934
1937
1940
1943
1946
1949
1952
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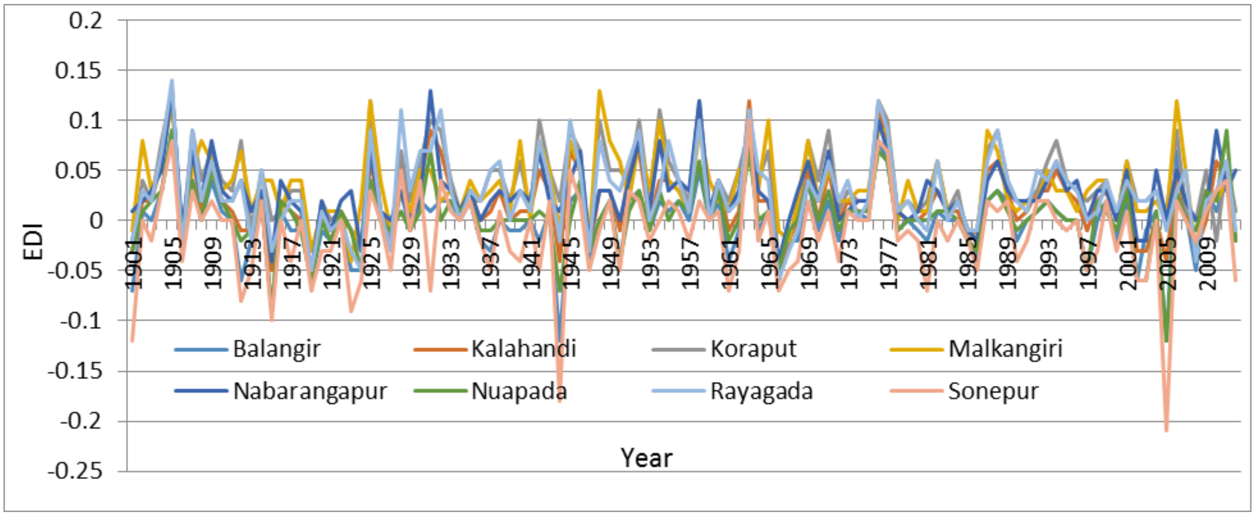
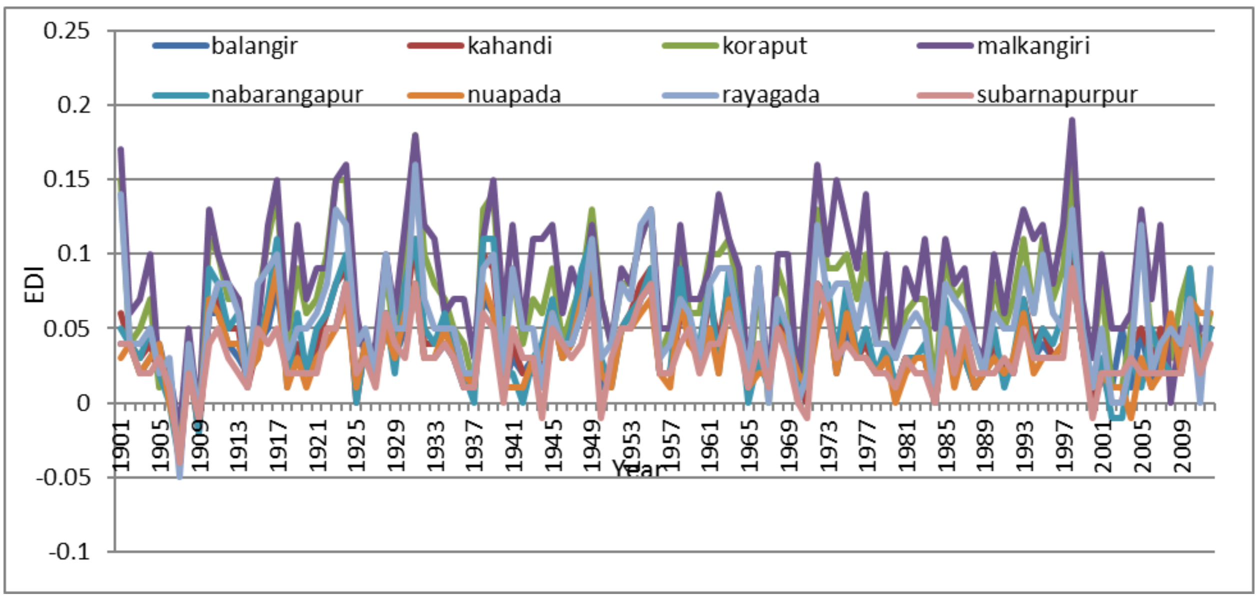
1958
1961
1964
1967
1970
1973
1976
1979
1982
1985
1988
1991
1994
1997
2000
2003
2006
2009
2012
Year

APPENDIX V: EDI plots for the month June and December



EDI plots for the month June



EDI plots for the month December

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